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## Central Eurasia: Earth Sciences

ECOLOGICAL CONSEQUENCES ON CHERNOBYL

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# SCIENCE & TECHNOLOGY

# USSR: EARTH SCIENCES

# ENVIRONMENTAL CONSEQUENCES ON CHERNOBYL

927N0030 Moscow PRIRODA in Russian No 5, May 91 pp 41-70

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Environmental Traces of Chernobyl

927N0030A Moscow PRIRODA in Russian No 5, May 91 p 41

[Article by L. M. Khitrov, head of radiogeochemistry laboratory, Geochemistry and Analytical Chemistry Institute, USSR Academy of Sciences, winner of the Lenin Prize, vice president of the Soyuz Chernobyl (Chernobyl Union)]

[Text] The accident at the Chernobyl nuclear power plant resulted in pollution of a considerable part of the European USSR with an area of more than 100 000 $km^2$, in which about 4.5 million people live, by artificial radionuclides. Now there is no one who doubts that this tragedy with respect to its global consequences was the greatest ecological catastrophe in the history of mankind, whose scale was far more grandiose than it would have been possible to visualize at first. For example, the long-lived radio nuclides $^{134}Cs$ and $^{137}Cs$ entered the biosphere in a quantity greater by a factor of 600 than as a result of the atomic bomb detonated at Hiroshima. And nevertheless, today, five years after the accident, the question may arise: other than the unprecedented tragedy of the catastrophe itself, what was new in the Chernobyl phenomenon?

On the one hand, each "small piece of Chernobyl" we once studied in other places and under other conditions: during global radioactive fallout from nuclear tests in the atmosphere, at the time of the accidents in the Southern Ural [See Footnote 1] and at nuclear power plants in Great Britain and the United States. But, on the other hand, there was never anywhere such a combination of factors which the Chernobyl catastrophe produced.

The specific character of Chernobyl, in particular, was that it was not a momentary process: the release of radionuclides into the atmosphere did not last for seconds (as in nuclear tests) or hours (as in the Kyshtym accident), but several days. During this time, as a result of complex physicochemical processes, in the damaged reactor there was a change in the composition of the effluent and also a change in meteorological conditions. All this resulted in an exceedingly complex, spotty pollution pattern.

The Chernobyl accident also was characterized by an unusually great quantity of "hot particles." They, to be sure, also were known earlier (for example, they were registered during global fallout), but Chernobyl particles were specific with respect to both quantity and their nature. They were formed during the fire in the fourth unit -- from burning fuel cells, the materials of the reactor itself and those materials with

which it was strewn. According to our estimates, not less than 70% of all the radioactivity in the near zone was associated with hot particles.

And nevertheless, despite the new data obtained in a study of the consequences of the Chernobyl accident, despite new methods and instruments, it must be admitted that all the scientific research here was based on investigations which had already been made: the bulk of the work rested on the shoulders of those scientists who had much experience in studying environmental radioactivity, in particular, on the shoulders of specialists of the USSR Academy of Sciences.

Among the promising scientific investigations related to study of the environment in territories affected by the accident the most important is the preparation of landscape-geochemical and radioecological maps containing data not only on the concentration of radionuclides, but also on their mobility. Such maps are becoming a reliable basis for radiogeochemical predictions.

Closely related to this problem is the study of the forms of presence and migration of radionuclides under real conditions. Whatever model experiments we might carry out in laboratories and in experimental areas, the pollution pattern was too nonuniform and the serious nature of prediction was too great for the work to be limited to this alone. A study of the forms of presence and migration of radionuclides is therefore a problem which will remain timely for many years to come.

And in conclusion, still another comment. During the three years since the accident all the scientific research associated with Chernobyl was carried out under conditions of increasing secrecy (the first reports, for example, were imprinted with the words "For Official Use Only," but later were stamped "Secret." It is difficult to say now why this was done: anyone who wanted to find out something, could nevertheless do so, but others were fed rumors fraught with disinformation. And only in 1989 was the decision made to publish openly everything about the accident at the Chernobyl nuclear power plant. Only a complete openness of all research will make possible maximal use of the scientific archives of a great many organizations engaged in study of the consequences of the accident both in our country and abroad.

Footnote

1. For example, see: An overview of the Kyshtym accident, PRIRODA, No 5, pp 47-75, 1990.

Physicomathematical Simulation of Behavior of Radionuclides

927N0030B Moscow PRIRODA in Russian No 5, May 91 pp 42-51

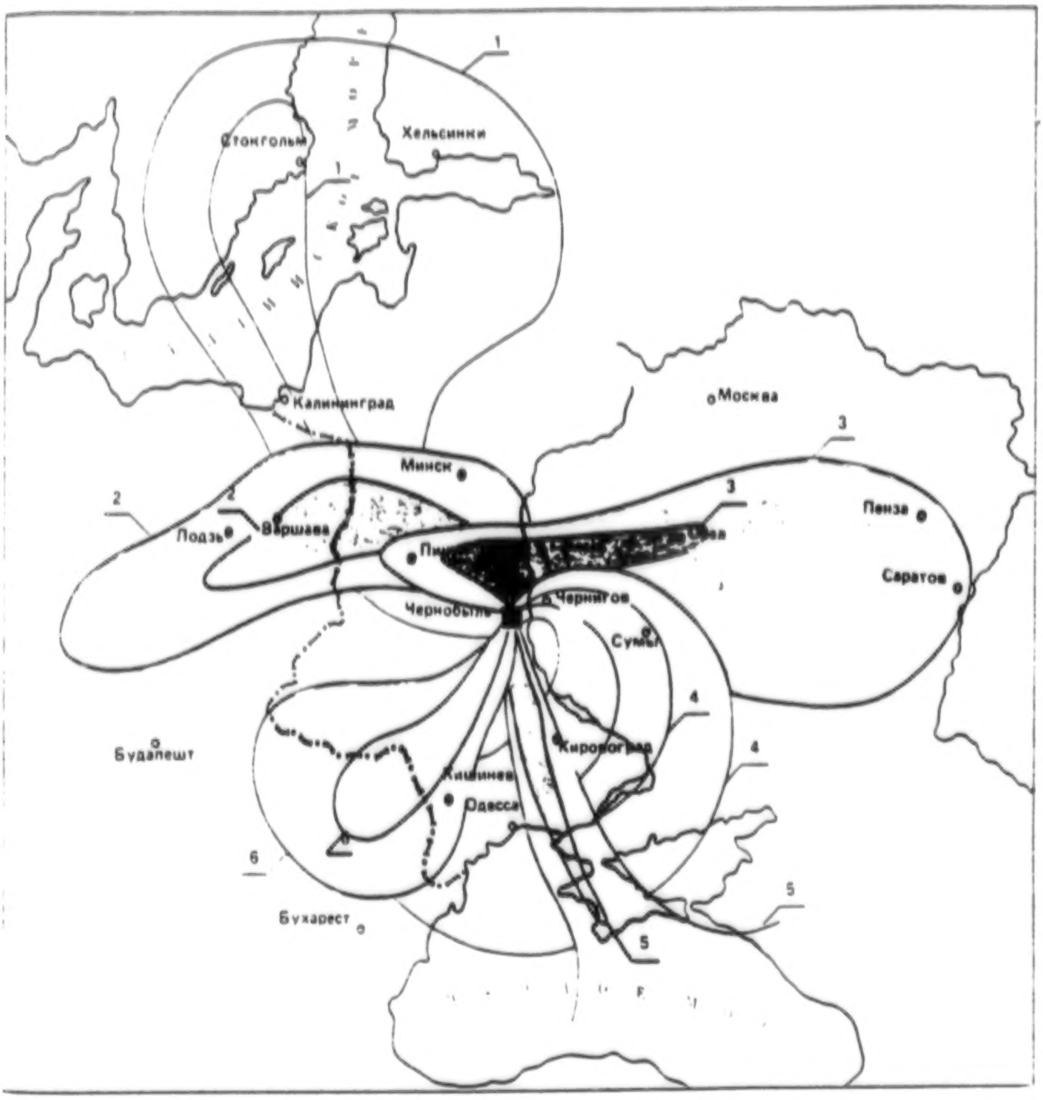
[Article by V. A. Borzilov]

[Text] From the first day after the accident the Tayfun Scientific Production Association and other institutes of the USSR State Committee for Hydrometeorology and Environmental Monitoring had to monitor the radiation conditions developing as a result of the propagation of radionuclides from the destroyed reactor. An aerial gamma survey was carried out for this purpose in a 30-km zone and special expeditionary detachments took samples which were then sent to the Tayfun Scientific Production Association and which were analyzed there for their content of radionuclides. Simultaneously the association received information from stations in the network of the State Committee for Hydrometeorology and Environmental Monitoring scattered throughout the country: from approximately 2000 stations on the intensity of the gamma dose, from 500 on the density of fallout of radionuclides on special sheets and from 100 on the concentrations of radionuclides in the air. Unfortunately, in the accident region itself the density of control points was low.

Since the active release of radionuclides from the destroyed reactor continued for approximately 10 days and during this time there was a considerable change in both the meteorological situation and the conditions in the reactor itself, it was difficult to analyze the complex pattern of formation of pollution fields using the inadequate and delayed information. Accordingly, immediately after the accident we proceeded to mathematical simulation of the atmospheric transport of radionuclides ejected from the reactor and their precipitation onto the underlying surface.

Several objectives were set. First, to understand how pollution was formed day after day. Second, to analyze how meteorological factors and the character of the source itself exerted an effect on the transport and precipitation of radionuclides. Third, to discriminate particularly polluted sectors for priority investigation.

It can be seen that from the very beginning it was necessary to evaluate the already prevailing situation, that is, to solve the diagnosis rather than the prognosis problem. The reason for this was technological unreadiness for carrying out computations at the time scale necessary for prediction.

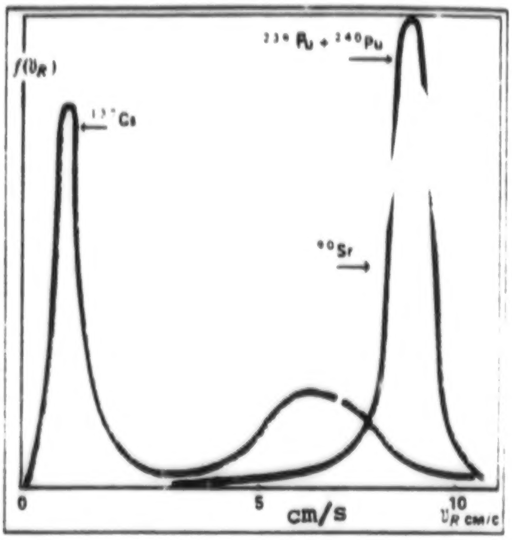



Principal stages in formation of track of radioactive fallout of $^{131}I$ on first days after Chernobyl accident due to change in meteorological conditions. The figures denote the computed fallout fields (tracks) from instantaneous releases of radionuclides; 1) 26 April 0000 GMT; 2) 27 Apr 0000 GMT; 3) 27 April 1200 GMT; 4) 29 April 0000 GMT; 5) 2 May 0000 GMT; 6) 4 May 1200 GMT. The intensity of the coloring qualitatively corresponds to fallout density.

By the way, in not one country of the world were their ready-to-use technologies for issuing a quantitative prediction for transport scales characteristic for this accident. Nevertheless, a prediction of the trajectories of transport of air masses was prepared both abroad and in our country (in particular, at the USSR Hydrometeorological Center).

Retrieval of Parameters of Source of Radioactive Pollution

Approximately two years prior to the Chernobyl accident at our association we began to develop methods for rapid reaction to accidental pollution. The basis for these methods was a set of models of atmospheric transport at different scales (200, 2000 and 4000 km). From the very beginning the models were oriented on use at a real time scale and use was made only of the standard meteorological information employed at the Hydrometeorological Center for weather prediction.



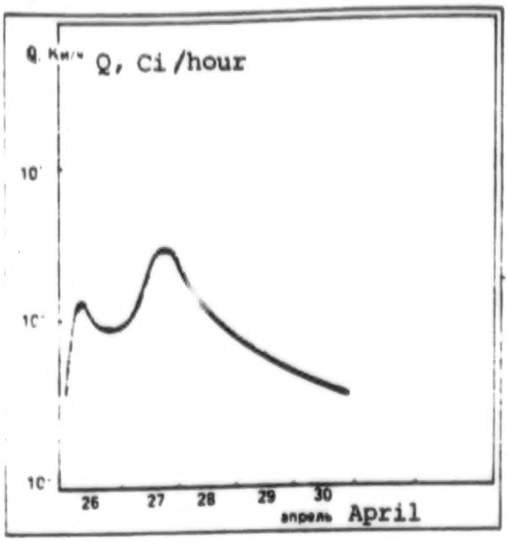




Figure at left: Distribution of long-lived radionuclides by rates of gravitational precipitation. Computations indicated that plutonium and strontium were propagated in the atmosphere predominantly on large particles (mean rate of precipitation about 10 cm/s), cesium -- same on both coarse and fine particles (about 1 cm/s).

Figure at right: Change in source intensity causing formation of field of pollution by $^{137}Cs$ in distant zone. In particular, during increase in the yield of this radionuclide on 27 April there was movement of air masses into regions of Belorussia, as well as Bryanshchiny and other oblasts in Russia.

As is well known, 4 times a day the Hydrometeorological Center receives data from all meteorological stations in the country and aerological sounding stations. On their basis an on-line data bank is organized containing temperatures and two wind speed components at altitudes about 1000, 1500, 2500 m, etc. at the points of intersection in a rectangular grid with grid squares 150 x 150 km. There also, at the Hydrometeorological Center, after solving the weather prediction problem for the next few days, a similar data bank is organized for 24, 36 and 72 hours in advance.

All this information could be transmitted through computer communication channels to the Tayfun Scientific Production Association and used for

diagnosis or prediction. The models mentioned above, which were based on solution of the ordinary three-dimensional turbulent diffusion equation with use of different numerical solution schemes, dependent on the transport scale, also were oriented on it. The winds speed values and diffusion coefficients entering into the equation were computed with allowance for the input information using models of the atmospheric boundary layer, also dependent on transport scale.

By the time of the accident the models were entirely ready to use. However, there was no on-line connection with the Hydrometeorological Center and magnetic tapes with a record of current information had to be transported 100 km from Moscow to Obninsk, where the association is located. Moreover, the models existed only in a scientific research version (that is, different corrections were introduced into them in the course of the work), but the computations were made on a YeS-1061 computer, not satisfying our needs with respect to many parameters.

All this made it impossible to solve prediction problems. But the greatest and most fundamental difficulty was the lack of objective information on the source. It could not be obtained primarily because there were no special technical facilities in a state of constant readiness for the case of an accident. Only individual measurements could be made. In particular, from an aircraft of the Applied Geophysics Institute, USSR State Committee on Hydrometeorology and Environmental Monitoring, it was possible to take an air sample directly from the "plume" -- this was on 27 April, but thereafter the aircraft was highly polluted and unsuitable for further work. Measurements also were made by specialists from other organizations (Physical Chemistry Scientific Research Institute imeni L. Ya. Karpov), Radium Institute, Tayfun Scientific Production Association and military organizations). However, all this was already after 5 May when active release had ceased.

On the first days very little was known about the source, for example, it was not known what quantity of radionuclides was ejected by the explosion and to what altitude. It goes without saying that information on the reactor from the first days after the accident was actively collected by specialists of the Atomic Energy Institute (AEI) imeni I. V. Kurchatov, but their information (fuel temperature, neutron fluxes, gamma field, etc.) was not suitable for the simulation of atmospheric transport. In particular, we had to know how the distribution of the aerosol particles emanating from the reactor changed with time with respect to size and radionuclide composition, as well as the altitudinal distribution of different particles in the plume.

In general, the lack of this type of information is characteristic for emergency situations when it is difficult to make precise measurements. Accordingly, even having special technical facilities it is necessary to be prepared for an inadequate knowledge of the nature of the pollution source and its retrieval using data from a measuring network, that is, solution of the inverse problem is required.

Expressed simply, we used the following procedure. First a solution was found for the direct problem of transport and precipitation of radionuclides for different sources (for different distributions of aerosol particles by size and composition, altitude, release intensity, etc.). Then from all the solutions we selected those which were most consistent with available measurements of the fallout of radionuclides onto sheets or the soil. The source parameters corresponding to the best solutions were accepted as the true parameters.

To be sure, this approach, due to the incorrectness of inverse problems, may lead to errors, and therefore we invoked different physical considerations and optimizing procedures. In addition, the dynamics of meteorological processes itself to a high degree favored the "regularization" of the source retrieval problem.

The fact is that during the time of active release (26 April-5 May) the wind shifted 360°. This made it possible when solving the inverse problem to discriminate the contributions of the source at different moments in time and to trace the day-to-day dynamics of the release. Computations showing the principal stages in formation of the track of radioactive fallout were made for a weightless impurity (the same, incidentally, as the behavior of $^{131}I$ was simulated) arriving in instantaneous impulses of an arbitrary intensity at times characterizing the restructuring of meteorological fields. It goes without saying that such a nature of the source is not realistic and is suitable only for a qualitative analysis.

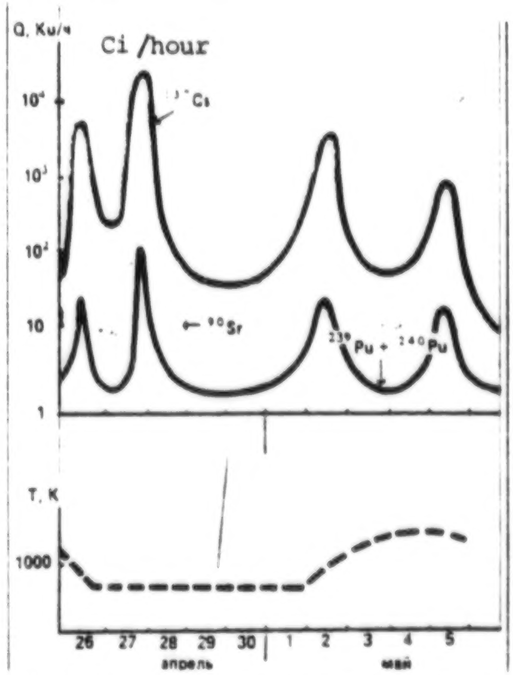
The characteristics of release of long-lived radionuclides, $^{90}Sr$, $^{137}Cs$, as well as $^{239}Pu$ and $^{240}Pu$ (total), were obtained by solution of the inverse problem. Judging from the rates of precipitation of the aerosol particles, the plutonium and part of the cesium were transported on large particles (most likely fuel particles) and had to settle in the near zone. Most of the cesium, however, was transported by small particles for considerable distances.

Based on an analysis of the meteorological situation and the source parameters, obtained by solution of the inverse problem, we will turn to the formation of pollution.

## Simulation of Atmospheric Transport of Radionuclides

The reactor explosion of 26 April resulted in a sharp release and subsequent escape of radionuclides in the form of fuel particles, aerosol particles and gases. During the 1/2 days which followed they were transported predominantly in a westerly, northwesterly direction, forming a broad track to the west. At this time the fuel temperature dropped and the intensity of the release decreased. Beginning at midday on 27 April the graphite in the reactor began to burn more intensively and the release of all the radionuclides, especially $^{137}Cs$, transported by gas and aerosol particles, increased. At this time the wind direction changed to northerly, and then, very rapidly, became northeasterly.

The precipitation of cesium also occurred on the trajectory of this transport, leading to the formation of the extensive Bryansk-Belorussian and Orlov-Tula-Kaluga spots. This also was favored by the precipitation falling during passage of the cloud.



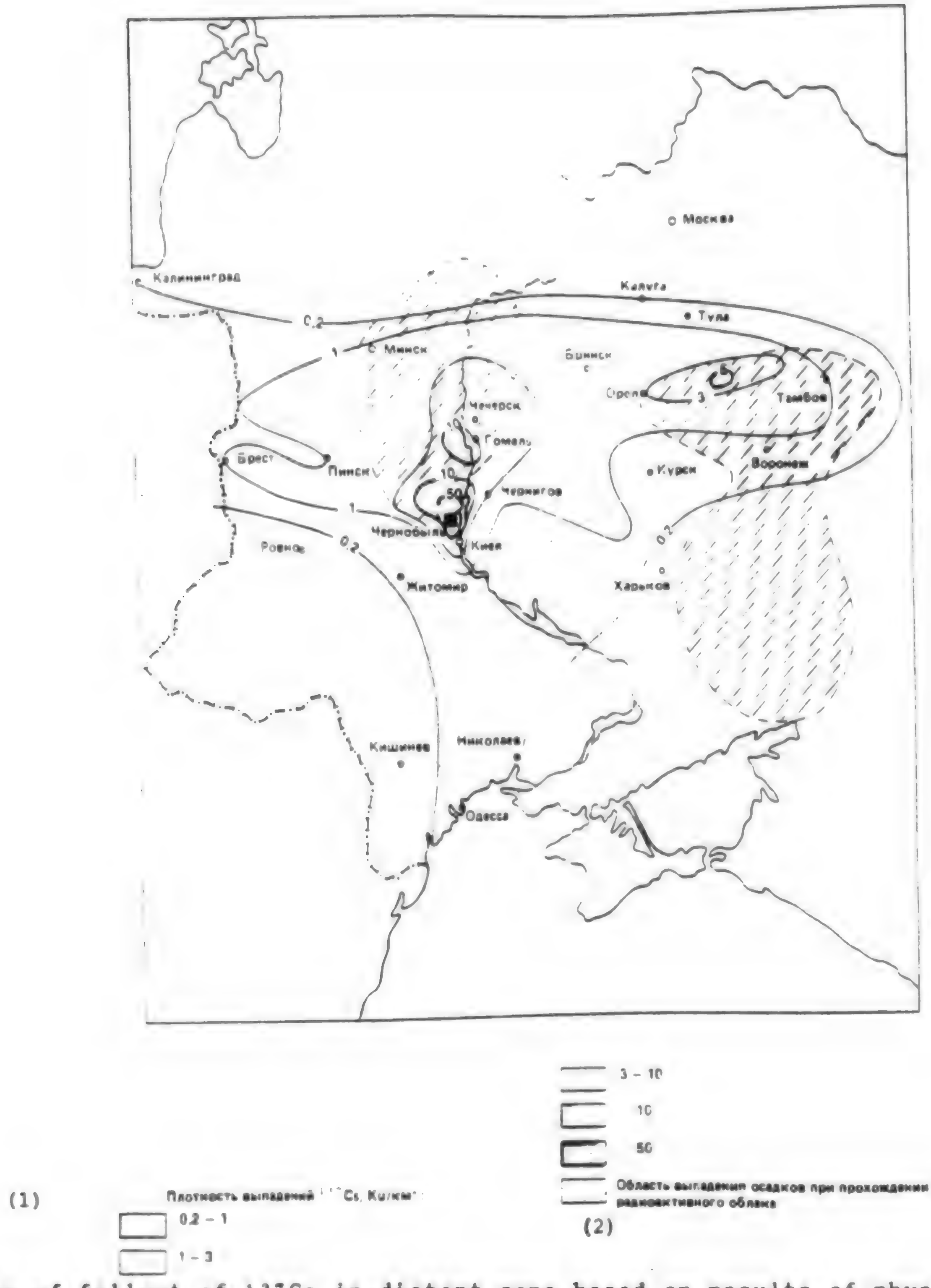

April May

Results of simulation of change in intensity of source of $^{137}Cs$, $^{90}Sr$, $^{239}Pu$ and $^{240}Pu$ transported on large particles and forming fallout fields in near zone (up to 100-200 km from reactor). At bottom -- change in fuel temperature (according to data from Atomic Energy Institute).

A second factor exerting an influence on the density of fallout in the region of the spots was the existence of extensive stagnant zones there. For example, at Chernobyl the wind speed at the altitude of the release (about 1000 m) attained 10 m/s, whereas in the regions of the spots it decreased to 1-2 m/s. This resulted in stagnation of masses of radioactive aerosol and together with the nonuniform falling of precipitation gave the effect of spottiness at different scales.

Such a thorough discussion of these details is attributable to the fact that the nature of the spots caused many disputes. It was even suggested that the Bryansk-Belorussian spot was the result of special work on the precipitation of the radioactive cloud for the purpose of not allowing it to reach Moscow. In actuality the spottiness was caused by a combinaation of meteorological factors and the special character of entry of radionuclides into the atmosphere.

However, we will return to the formation of the pollution fields. The strewing of the reactor with materials began on 27 April and on 28-30 April the intensity and altitude of the release decreased substantially. At this time the shifting of the wind continued in a clockwise direction




Map of fallout of $^{137}Cs$ in distant zone based on results of physico-mathematical simulation. Although this map is not as detailed as the official map of strontium pollution produced later, the features of the real field of distribution of radioactive tracks are apparent from it. [Key on next page]

KEY:

1. Fallout density, $^{137}Cs$, Ci/km$^2$
2. Region of falling of precipitation during passage of radioactive cloud

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from east to south and therefore territories to the southeast of the reactor were relatively clean. Beginning on 2 May, when heating began in the reactor, associated with a decrease in heat transfer, aerosol particles periodically burst into the atmosphere (maxima on 4 and 5 May). During these releases a northerly wind prevailed, resulting in the formation of a southerly track.

That is how we evaluate the situation on the first days after the accident today. And now we will turn, as a comparison, to the computed map of $^{137}Cs$ fallout in the distant zone. This map, obtained by physicomathematical simulation, reflects the totality of physical processes which were mentioned above. It goes without saying that it is not as complete as later maps [See Footnote 1], but it already reveals the features of the real field of radioactive pollution: westerly, northwesterly and southerly tracks, as well as three large spots (central -- Chernobyl, in Belorussia and Russia).

The most important consideration is that this map was constructed in mid-May 1986 when almost all the forces were concentrated in the 30-km zone and near it and only individual measurements at control points of the State Committee for Hydrometeorology and Environmental Monitoring indicated possible trouble in remote regions. Later, however, in mid-May, the Tayfun Scientific Production Association organized an expedition for taking soil samples along the line Bryansk-Gomel-Baranovichi. Their analysis laid a beginning for a detailed investigation of the extensive Bryansk-Belorussian spot, work continuing to this very day.

At approximately this same time work began on investigation of cesium pollution in the Orlov-Tula-Kaluga spot. In other words, we obtained a computed pollution map at the time when there was a practical need for it and when it could be used to correct the control instruments. This is an entirely specific example of solution of the problem of diagnosis of an emergency situation by physicomathematical simulation methods on an ongoing basis.

Different estimates of the total yield of radionuclides, obtained both as a result of both physicomathematical simulation and integration (that is, calculation of fallout onto the underlying surface) in general give consistent values. Only in individual cases does the discrepancy attain 100%, which considering the general inadequacy of data and lack of information on the source is an entirely reasonable accuracy. And still another important point. When calculating the absolute yield of radionuclides it is important to take into account data not only for

the territory of our country, but also for other countries. Abroad many researchers were engaged in the simulation of the transport and precipitation of radionuclides after the Chernobyl accident, but in our opinion the most important processes were taken into account most completely in the studies of the groups headed by H. Epsimon of London Imperial College (Great Britain) and N. Goodikens of the Livermore Laboratory (United States). In these studies reliance is on a description of pollutions in Western Europe and at global scales respectively. Their methods and approaches in general are similar to ours. In particular, like us they solved the inverse problem, but using data on pollution outside the territory of our country.

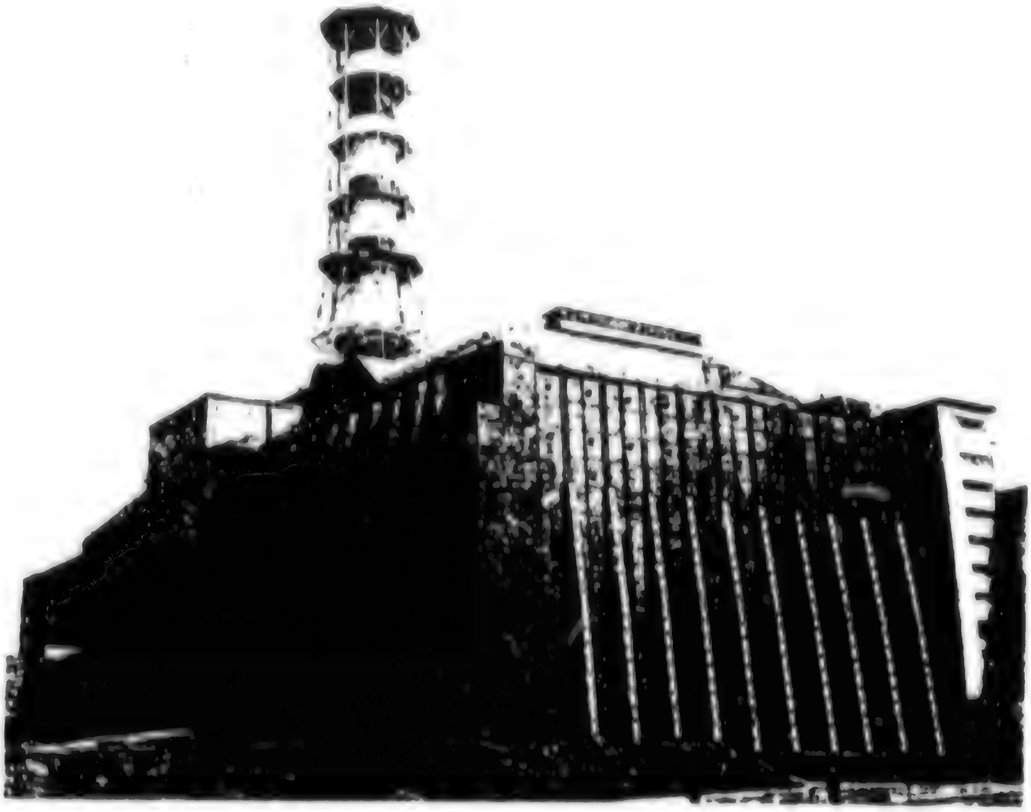
After a comparison of the results of simulation at different scales it became clear that in retrieving the source we allowed a number of errors. For example, the simulation for Western Europe indicated that further transport of $^{137}Cs$ was not only by fine particles, but also by gas, and this phase, causing the pollution of Western Europe, accounts for about 1 MCi, that is, as much as fell in the territory of our country with aerosol particles. However, the simulation of transport at global scales made it possible to clarify that in the first explosion a considerable quantity of radionuclides was released to an altitude of about 10 km. This cloud was first propagated southward and then bent around half the Earth and even caused a small increase in the radioactivity level in the United States.

All the data on the source were completely reconciled in late 1989 at the First International Working Group on Serious Accidents and Their Consequences, called on the initiative of the nuclear societies of the USSR and the United States. At that meeting there was a discussion of processes in the reactor, as well as the balance of radioactivity and radioactive fallout: how much had accumulated in the reactor prior to the accident, remained in it and beneath it after the accident, fell at the industrial site, distant from the station and in general over the territory of Europe and over the entire globe [See Footnote 2].

## Simulation of Pollution of Water Bodies and Soils

The next stage in our work on the simulation of transport and precipitation of "Chernobyl" radionuclides was related to the secondary pollution of soils and water bodies. The latter problem was particularly acute for the Chernobyl accident because both in the 30-km zone and in the Bryansk-Belorussian spot there is a far-flung river network, the watersheds of the Pripyat and Dnepr, which supply water to 40 million people living below the Dnepr cascade.

The problem of the washing away of radionuclides from watersheds was equally timely. It was not without reason that from the first days after the accident work began on shoring up the banks for protection against possible rain-induced sheet erosion.



Sarcophagus over fourth unit at Chernobyl nuclear power plant.

It was important to evaluate what could be expected if there were heavy summer rains and intensive spring snow melting. The most different estimates were discussed: from quite optimistic, based on observations of global fallout of the products of nuclear shots and not portending substantial sheet erosion, to extremely pessimistic, predicting, for example, that all the strontium would be washed from the Pripyat floodplain into Kiev Reservoir.

The strategy of water conservation measures depended on how these events came to pass. In particular, it was proposed that the waters of the Pripyat be diverted into the Dnepr in order to bypass the 30-km zone or that a dam be constructed at the mouth of the Pripyat in order to "lock in" all the radioactivity there. These, to be sure, are extreme measures. First of all, they are exceedingly costly and second, in completing radioactive pollution they would ruin the entire 30-km zone. And this could go on and on.

The Tayfun Scientific Production Association therefore had to make a prediction of secondary pollution of this zone by radionuclides under the most unfavorable meteorological conditions: abundant rains, snow melting, etc. Since it was clear from the very beginning that the Chernobyl release was unique and that months or even years would be spent on its study, whereas a prediction was required "today,"

formulation of a mathematical model which would sufficiently adequately describe the behavior of radionuclides in the zone became the most important consideration.

Our model was based on classical concepts that radionuclides can be in dissolved, exchange-sorbed and irreversibly sorbed states and also enter into the composition of insoluble fuel particles. It also was necessary to take these four phases into account in order to describe correctly their vertical movement along the profile, surface runoff of radionuclides in a dissolved state and with soil particles, as well as transport in rivers.

After writing systems of equations describing these processes we were convinced that everything is "controlled" by three parameters: content of exchange forms of radionuclides, content of fuel particles and distribution coefficients (content of exchange forms) for the "water-soil," "water-bottom deposits" and "water-suspended matter" systems. They had to be measured.

Samples were taken from the entire 30-km zone. Later, in the laboratories of the Tayfun Scientific Production Association, the forms of presence of radionuclides in the samples were investigated and the distribution coefficients were measured.

Thus, in the first stage we obtained the parameters of the model. Thereafter (but more precisely, simultaneously) we went into the field and at different distances from the reactor prepared several test areas for in situ experiments. The summer was very dry and we "sprinkled" the test areas using a hose running from a fire engine. First the content of radionuclides in the test area was measured and samples were taken for laboratory determination of the forms of presence of radionuclides. After determining the full hydrological regime with such artificial watering, we took samples in the runoff, which made it possible to determine the sheet erosion coefficient.

Ideally the experiment would have to be carried out in approximately a hundred test areas. It would be necessary to obtain the sheet erosion coefficients, enter them into the model and describe how everything flows down along the rivers. But due to the difficult conditions (high activity, heat, poor organization, etc.) we could carry out only a series of 10 experiments at three points. This made it possible to check the model. And when we were convinced that the model was adequate the need for experiments in the entire zone disappeared. We only measured those parameters which had to be embodied in the model, flying around the territory in helicopters and taking samples.

Thus, the first part of the problem was solved: we simulated how radionuclides during the falling of rain or the melting of snow enter into the depths of the soil and are washed away by surface runoff into rivers. We also naturally checked this model in laboratory experiments, carrying out several column experiments and clarifying how the vertical distribution develops.

After coming to grips with this, it was necessary to work out a model of the behavior of radionuclides in the river, with its specifics, calibration parameters, etc. At that time we could not measure all the necessary parameters for rivers and only one simple assumption was made, taking into account that the values of the distribution coefficients and the content of exchange forms in the river were the same as on the shore. To be sure, this was stretching it, but we had to use this approach.

Thus, it was necessary to calibrate two important physical parameters: coefficients of exchange of dissolved radionuclides between the bottom and water and on suspended particles. We developed a network for monitoring the concentration of radionuclides at river mouths (on suspended matter and in dissolved form). By comparing the results of these observations and model computations we determined the sought-for parameters, that is, prepared a prediction.

We broke the entire territory into 37 watersheds. We characterized each of them by several parameters (distribution coefficients, content of exchange forms and fuel particles) and gave a hydrological prediction for each: how much water soaks in and how much is lost as surface runoff, and also how much soil will be washed away. The model also embodied the characteristics of rivers. And we calculated all this for different meteorological scenarios.

The results indicated that there was no threatening situation. This was true for both strontium and cesium. However, this became clear as soon as we saw in what forms these elements were present. The fact is that approximately 10-25% of the strontium was in the soils in an exchange form. However, in global fallout up to 75% of the strontium was in a soluble form and the sheet erosion coefficients did not exceed 1%. Accordingly, here also higher levels should not be manifested. It is true that in this case there was a specific situation associated with inundation of the floodplain: possibly due to the stagnation of water on the floodplain strontium might be dissolved and all washed away.

In order to understand the extent to which this hypothesis was correct we calculated everything for floodplain conditions (for confirmation first that the model was applicable there) and we found that there also should be no catastrophic levels in this case. Thereafter it was decided not to plan a bypass canal and it was decided to cease construction and further work on small dams.

Everyone awaited the first spring with anxiety. A good prediction was prepared at Leningrad State Hydrological Institute, on which our studies also were based. We once again refined our results, analyzing several possible snow melting scenarios. It was necessary to understand which is "more advantageous," rapid or slow melting of the snow, so that proceeding on this basis recommendations could be made on snow retention, strengthening of various dams, etc. During the high water of 1987 we organized a monitoring system on all small rivers in order to

trace the development of events and also to check to what degree our model corresponded to reality.

A fairly good agreement was obtained: the maximal discrepancy was by a factor of 2-3. We also were able to trace the passage of the peak of the high waters and the "stirring up" of radionuclides (to be more precise, their retention in suspensions). But this was not the end of our work. Such an important problem as form transformation remained open. Indeed, in the first predictions we considered a short time interval and this problem concerned us little at that time. However, proceeding to a long-range prediction, we postulated an undeviating decrease in the sheet erosion coefficient and entry of radionuclides into rivers due to their exchange forms arriving at deeper levels. We calculated that each year the entry of radionuclides into the rivers would decrease by a factor of almost 1.5. Unfortunately, this was not confirmed: everything remained at approximately the same level.

Most likely this was caused by a change in the forms of presence of radionuclides due to the destruction of fuel particles and the entry of strontium in a dissolved form. This, to be sure, was a hypothesis. Specialists still had to reckon with the fuel particles in order to understand how intensively strontium in an exchange form enters into the environment. Could some surprises await us here? And so it seemed evident that now the most important consideration was obtaining reliable information on the penetration of radionuclides into the subsurface hydrosphere.

Role of Simulation in Emergency Situations

In conclusion I would like to express several general considerations on the role of physicomathematical simulation in emergency situations. At the time of any major accident one of the priority problems is a lessening the negative impact of pollution on human health and on the environment. This requires the most rapid possible estimate of the scales of pollution, a determination of the places from which people had to be evacuated at once and where at some given time it would be possible to take only half-measures (imported food products, deactivation of soils, switching to other water supply sources, etc.). It was important not only to comprehend the developing situation, but also to predict how tens and hundreds of factors (wind, rain, ground water movement, chemical transformations, etc.) would exert an influence on the concentration of pollutants in the future. It is evident that mathematical simulation of their behavior in the environment is the only means for preparing such predictions.

It is less evident that mathematical simulation is applicable for evaluating the current status of the environment. It would seem that this problem can be solved by directly measuring the concentrations of pollutants in samples of air, soil, water, biological objects, etc. However, the time factor here is very important: in the case of enormous scales of pollution, as in the case of the Chernobyl accident, or when analyses of samples are very work-intensive (such as with pollution by

dioxin), a time loss in preparing pollution maps by instrumental methods is inevitable. Here, without question, mathematical simulation will be of assistance. Moreover, its results will favor optimization of operation of the measuring system because the samples can be taken primarily in those regions where, according to computations, the pollution levels are especially high.

And, in general, it is impossible to compare traditional measurements and physicomathematical simulation: computations must be used in directing and coordinating the functioning of pollution monitoring facilities and measurement results must be used in correcting computations, etc. Only with such an approach can mathematical simulation cope with its new role: facilitating the adoption of operational decisions at the time of accidental pollution.

In order to perform this role the mathematical models must not only adequately describe the principal processes, but also do this on an on-line basis, that is, when there is still need for computation results. If one speaks of Chernobyl, this was minutes and hours for warning the inhabitants of Pripyat, hours and a day for warning the inhabitants of distant regions, several days for evaluating the overall pattern of terrain pollution, weeks and months for evaluating secondary effects (wind deflation or sheet erosion of radionuclides), etc.

It goes without saying that each of these scales must have its own model describing different processes with corresponding detail, but they all require that the input data and parameters be obtained on a timely basis. This means that there must be a corresponding technology for the collection, transmission, storage, processing and output of information, as well as software for interaction between models and information. But this is not enough, since in some cases it is impossible to foresee what pollutant will be released as a result of an accident. Accordingly, methods are necessary for the rapid evaluation of model parameters (rates of absorption of pollutants by soils, their transformation, migration, etc.) as functions of the physicochemical properties and parameters of the environment. Such an evaluation may require special laboratory and field experiments.

Thus, for an on-line analysis and prediction of any accidental pollution it is necessary to have:
-- a set of mathematical models of the behavior of pollutants in the soil, water and air for different space and time scales:
-- computer communication lines and on-line banks for the storage of current meteorological and hydrological information, as well as data on the pollution of different objects in the environment;
-- data banks for environmental regime information (geographical maps at different scales, characteristics of watersheds, rivers, relief, landscapes, soils, etc.);
-- data banks on the physicochemical properties of pollutants;
-- an informational support program package;
-- laboratory and field experiment teams.

Unfortunately, even five years after the Chernobyl accident in our country there are only individual elements of such a system, these belonging, moreover, to different departments.

## Footnotes

1. Reference is to pollution maps of the European USSR by the long-lived radionuclides $^{90}Sr$, $^{117}Cs$, $^{239}Pu$ and $^{240}Pu$, prepared by the USSR State Committee for Hydrometeorology and Environmental Monitoring (for example, see Yu. A. Izrael, NAUKA I ZHIZN, No 9, pp 28-29, 1990).

2. For further details see: Four years after the explosion, PRIRODA, No 11, pp 64-90, 1990.

Biographical Data Concerning Author

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Radioactive Pollution of Dnepr Basin

927N0030C Moscow PRIRODA in Russian No 5, May 91 pp 52-56

[Article by O. V. Voytsekhovich]

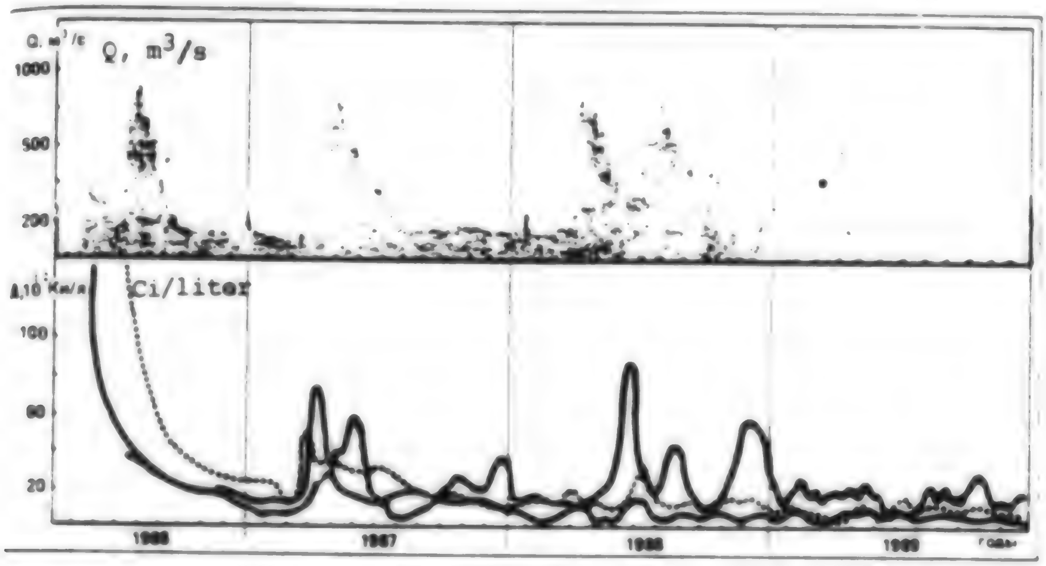
[Text] Tens of millions of people have become anxious due to radioactive pollution of rivers, reservoirs and lakes as a result of the accident at the Chernobyl nuclear power plant. Among the population ideas prevail that the radioactivity of the water is 10 times greater than the real levels, in many cases the people are not briefed concerning these levels and their fear is entirely understandable. Many feel that it is impossible to bathe and catch fish in the rivers and reservoirs, much less drink tap water.

Public appeals have been made to lower the Dnepr reservoirs, to dredge the silts from the bottom of water bodies and bury them, to divert the runoff of the Pripyat into the Dnepr by canals above the pollution zone, and also to carry out other costly measures without adequate ecological and economic validation.

Now, five years after the accident at the Chernobyl nuclear power plant, much is already evident. Water is not the principal reason for the internal and external irradiation of man -- it accounts for only about 5% of the sum of all sources (for the most part these are food products). It has become clear that costly technogenic water conservation procedures in the Chernobyl nuclear power plant zone (dams, weirs, pits in rivers, filtration curtains, etc.) have not greatly reduced the radioactivity of the waters. However, an analysis of natural processes in water bodies has revealed their high capacity for self-purification. The principal task of specialists now is therefore to make a detailed study of the processes and paths of water migration of radionuclides, known sources and possible future sources of entry of radioactive runoff into the Pripyat and Dnepr, and to direct efforts to the pinpointing of sources. Only on such a basis can there be an efficient scheme for and realization of the water conservation concept and also a correct prediction of the effectiveness of measures capable of improving conditions.

A solution for this problem was sought by many specialists of the USSR State Committee for Hydrometeorology and Environmental Monitoring, Ukrainian Ministry of Water Management, USSR Ministry of the Nuclear Power Industry, USSR Academy of Sciences and other institutions and departments. Already in May 1986 the organizations of the USSR State Committee for Hydrometeorology and Environmental Monitoring began a systematic study of the radioactive pollution of waters for predicting

water quality in Kiev Reservoir and the reservoirs lying downstream on the Dnepr, as well as possible unfavorable conditions for the washing of radionuclides into them. It was necessary to estimate the density of pollution in the principal watershed areas and in a short time to analyze the characteristics of rain-induced and snow melt runoff and the erosional indices of watersheds. Tens of experiments were carried out for this purpose in the zone of the Chernobyl nuclear power plant for estimating the washing away of radioactivity with water and solid particles for different types of soils and polluted landscapes. The principal result of work during this period was a system for the radiation monitoring of water bodies and prediction of under what possible conditions the radioactive pollution of reservoir waters would not exceed the maximal admissible levels stipulated in the interim radiation safety norms (RSN 76/87) in the USSR: $4 \times 10^{-10}$ Ci/liter for $^{90}Sr$) and $1.5 \times 10^{-10}$ Ci/liter (for $^{137}Cs$). It is true that many radio-ecologists consider these norms to be unsound and prepared on the basis of economic, not sanitary-hygienic considerations. The preaccident background levels of water pollution by these radio nuclides were $10^{-13}$–$10^{-12}$ Ci/liter.




years

Discharge Q of Pripyat waters at Chernobyl (at top), content A -- $^{137}Cs$ in water (dashed curve), on suspended alluvium (solid curve), $^{90}Sr$ in waters (color).

Even today $^{90}Sr$ and $^{137}Cs$ are the principal radionuclides polluting the waters. Their content in the Pripyat and in the Dnepr above Kiev Reservoir during the years after the accident was highly dependent on the nature of pollution of the watersheds on which the so-called slope runoff of waters into rivers was formed after the melting of snow and rains and also on the conditions for the inundation of river floodplains in regions with a high density of radioactive pollution after the accident.

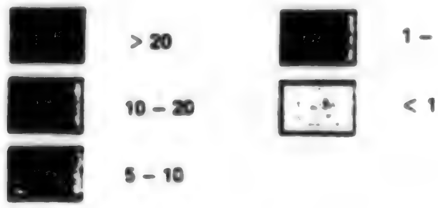
In general, however, at the time of high waters and after them, as well as when there are rain-induced floods, the content of radionuclides in

Ladizhichi

Pripyat River

Dnepr River

Density of pollution, Ci/km$^2$:



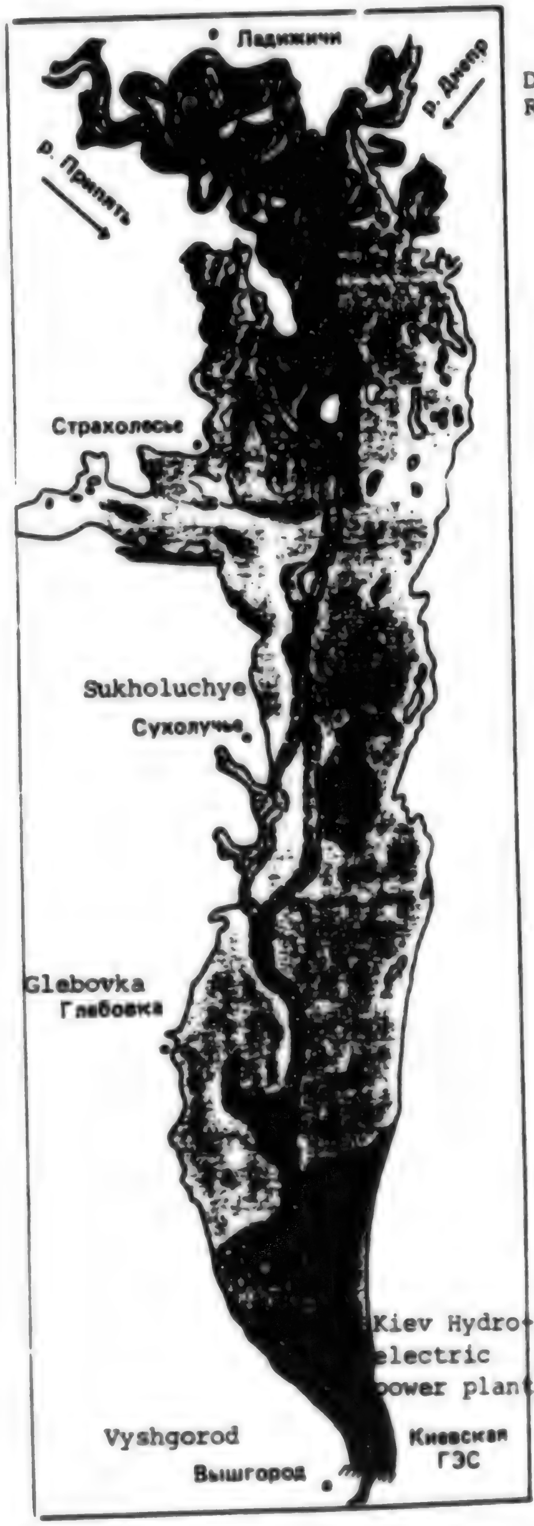

Strakholese

Sukholuchye

Glebovka

Kiev Hydroelectric power plant

Vyshgorod




$^{137}Cs$ content in bottom sediments of Kiev Reservoir (total area 922 km$^2$, total cesium content 2800 Ci, mean density of pollution 2.8 Ci/km$^2$). The deep-water sectors (and in particular, the old channels of the Dnepr and Pripyat) are the most polluted, as are the zones of maximal accumulation of sediments (flooded sectors along the Pripyat, sector of reservoir near dam), where silty alluvium is precipitated. The map was prepared in 1990 at the Ukrainian Hydrometeorological Institute.

the rivers increases, but in reservoirs the level is considerably lower and decreases with increasing distance from the place of river inflow.

This occurs not only due to the dilution of polluted river waters by the purer water of the reservoir, but also due to the precipitation here of radioactive suspended particles, as well as the adsorption of radionuclides by bottom deposits and their accumulation by hydrobionts. As indicated by observations, solid particles of suspended matter in rivers may carry from 30 to 70% of the total runoff of cesium, which as a result of sedimentation to a considerable degree precipitates out and is held in bottom deposits.

Cesium adheres particularly tenaciously on silty and clayey particles and therefore the particular location of polluted sediments in a water body may substantially lower the level of water pollution. The transport of sediments in rivers exerts virtually no significant influence on the transport of strontium.

The capacity of soil particles and river sediments to fixate such radio isotopes as cesium, cerium, plutonium and other radioactive pollutants served as a basis for the idea of constructing bottom traps in the Pripyat for the interception of suspended radioactive matter transported by water. They constituted large deep "open pits" in the river channel where due to the dropping of current velocities sediments should be precipitated, and radionuclides together with them. Unfortunately, however, the efficiency of the traps was insignificant because a great percentage of the radionuclides is sorbed on very small particles (less than 50 $\mu$m), precipitating only at very low rates. The depths and lengths of these "open pits" did not suffice for a sufficient quantity of such particles to precipitate in them. During a year these "open pits" intercepted only 5-10% of the cesium transported by the river. The Dnepr reservoirs in this sense "operated" incomparably more efficiently.

Since radionuclides for the most part are sorbed by fine ground particles, coarse sandy channel sediments of rivers (even in very polluted regions near Pripyat), as well as the sandy beaches of rivers and reservoirs, usually remain relatively pure; on the other hand the abyssal zones of water bodies with silty particles are polluted far more strongly. On the map of radioactive pollution of the floor of Kiev Reservoir which we compiled, on the one hand there are zones of increased bottom pollution in places of precipitation of Pripyat sediments and in deep sectors of the water body, and on the other hand, there are relatively pure shallow-water sandy zones where silts are not accumulated. During the years following the accident there was no appreciable displacement of the zone of pollutants into the lower reservoirs.

Observations indicated that by the beginning of 1990 the Pripyat and Dnepr carried into the cascade of reservoirs about 4000 Ci $^{137}Cs$ (1000 Ci of these with sediments) and 2500 Ci $^{90}Sr$. About 80% of the cesium entering Kiev Reservoir with river runoff was accumulated in the bottom deposits of the entire cascade. However, a high percentage of the strontium was carried straight through the cascade and entered the Black Sea. This, nevertheless, did not significantly change its content in sea water in comparison with the background formed in the 1960's during tests of nuclear weapons. We estimate the quantities of $^{137}Cs$ in all the reservoirs at approximately 4000 Ci, but $^{90}Sr$ -- not more than 1000 Ci.

Thus, as a result of sedimentation and processes of adsorption of radionuclides by the bottom the waters of the Dnepr reservoirs are considerably self-purified and the polluted bottom sediments are covered by purer sediments. In some sectors the thickness of the sediments settling after the accident has already attained several centimeters, which is slowing the exchange of radioactive pollutants between bottom deposits and the water.

In 1989 the pollution of Dnepr reservoirs with $^{137}Cs$ radionuclides varied from $(1-3) \times 10^{-11}$ Ci/liter at the mouth of the Pripyat to $0.5 \times 10^{-12}$ Ci/liter in the Dnepr at Kherson. The $^{90}Sr$ content is more "even" from Kiev to the Dnepr-Bug estuary and varies in the range $(5-15) \times 10^{-12}$ Ci/liter.

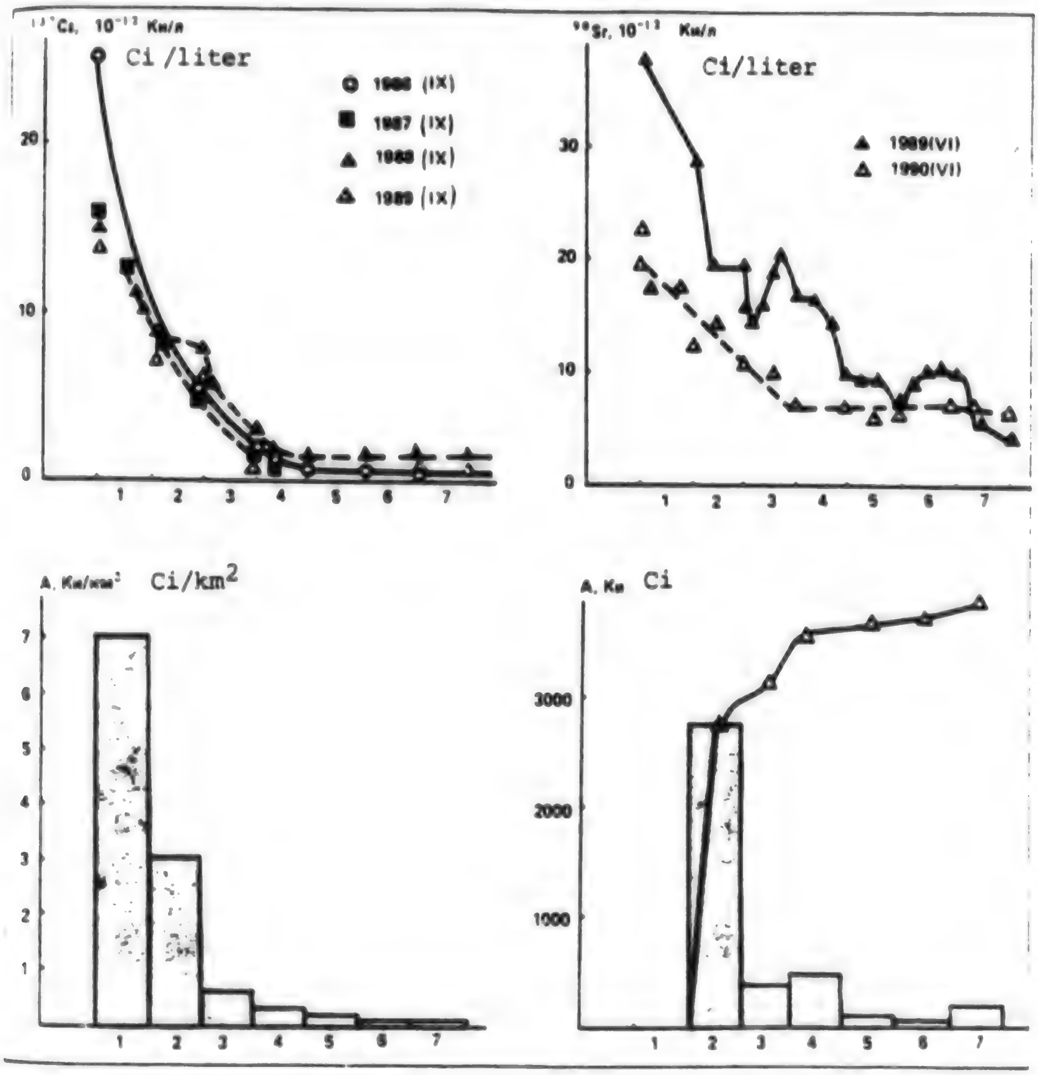
In 1990 the pollution level in cascade waters decreased further by a factor from approximately 2 to 14.

Research of recent years has indicated that although the accumulation of $^{137}Cs$ in the bottom deposits of the reservoirs is continuing. The main problem in their radioactive pollution is related to the $^{90}Sr$ content in the waters. The entry of strontium into the Dnepr cascade is dependent on its washing away from polluted territories both in the 30-km zone of the Chernobyl nuclear power plant and beyond its limits.

During 1988-1989 up to 40% of the strontium entering the Kiev Reservoir with the runoff of the Pripyat was formed in the drainage basins of Belorussia; the remainder entered from the 30-km zone, from the floodplain territories and water bodies in the immediate neighborhood of the accident site. In the waters of the Dnepr a high percentage of the radioactive runoff is formed in the Sozh River basin.

The most dangerous sources of inflow of radio nuclides into the reservoirs are the floodplain of the Pripyat near the Chernobyl nuclear power plant and the filtering waters of the cooling water body. Here the aerosols falling from the radioactive cloud on the first day after the accident formed zones of pollution with a high content of "hot particles" of nuclear fuel containing uranium oxides and graphite fragments. As a result of the continuing mechanical destruction of fuel aerosols and the leaching of radionuclides from "hot particles" active processes of transition of fission products into water-soluble and

exchange forms are observed, in particular, for $^{90}Sr$, poorly held in soils and mobile in an aqueous medium.




Radioactive pollution of reservoirs of the Dnepr cascade: at top -- content of cesium and strontium in water, at bottom -- density of bottom pollution by cesium (at left) and its reserve at bottom (at right) in 1989. The curve in the lower right part of the figure is the total reserve in all reservoirs: 1) mouth zone of Pripyat and Dnepr, 2) Kiev, 3) Kanev, 4) Kremenchug, 5) Dneprodzerzhinsk, 6) Zaporozhye, 7) Kakhovo Reservoirs.

During the years since the accident the floodplain has almost not flooded at the time of high water due to the low flood waters. Mathematical simulation and experiments indicate that even extremal sheet erosion of $^{90}Sr$ does not result in Kiev Reservoir in a level exceeding the maximal admissible pollution levels (according to RSN [Radiation Safety Norms] 76/78). However, the flooding of this territory may nevertheless lead to additional pollution of the waters of the Dnepr cascade and may aggravate the radioecological problems associated with this.

Among the several variants of the confinement of radionuclides here preference was given to the building up of the floodplain with alluvium into the body of a levee and strengthening the shore zone with sand from the channel. A sector surrounded by a levee would be planted in shrubs. Provision is made for a drainage system in order not to allow swampification of the territory. Other measures also were proposed for reducing the transport of $^{90}Sr$ from the polluted territories and pollution of Dnepr waters, which under extremal conditions will make it possible to reduce the strontium content in them by a factor of 3-5. This is particularly important for the lower Dnepr reservoirs, which are used for the irrigation of agricultural crops. Incidentally, research indicated that the use of Dnepr waters for irrigation for the time being is not increasing the individual dose of irradiation of the population. After the shutdown of the Chernobyl nuclear power plant there was no longer any need for functioning of the cooling water body. The filtering of polluted waters from it will cease with time so that still another source of radioactive runoff is disappearing.

The ecological state of Dnepr reservoirs is now determined not so much by radioactive substances as by the millions of cubic meters of unpurified industrial waste waters being dumped into the Dnepr and the ecological problems of the Dnepr water system cannot be solved without taking this into account and also without learning to evaluate correctly the risk from the introduction of various water conservation measures.

Biographical Data Concerning Author

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Plutonium in Soils

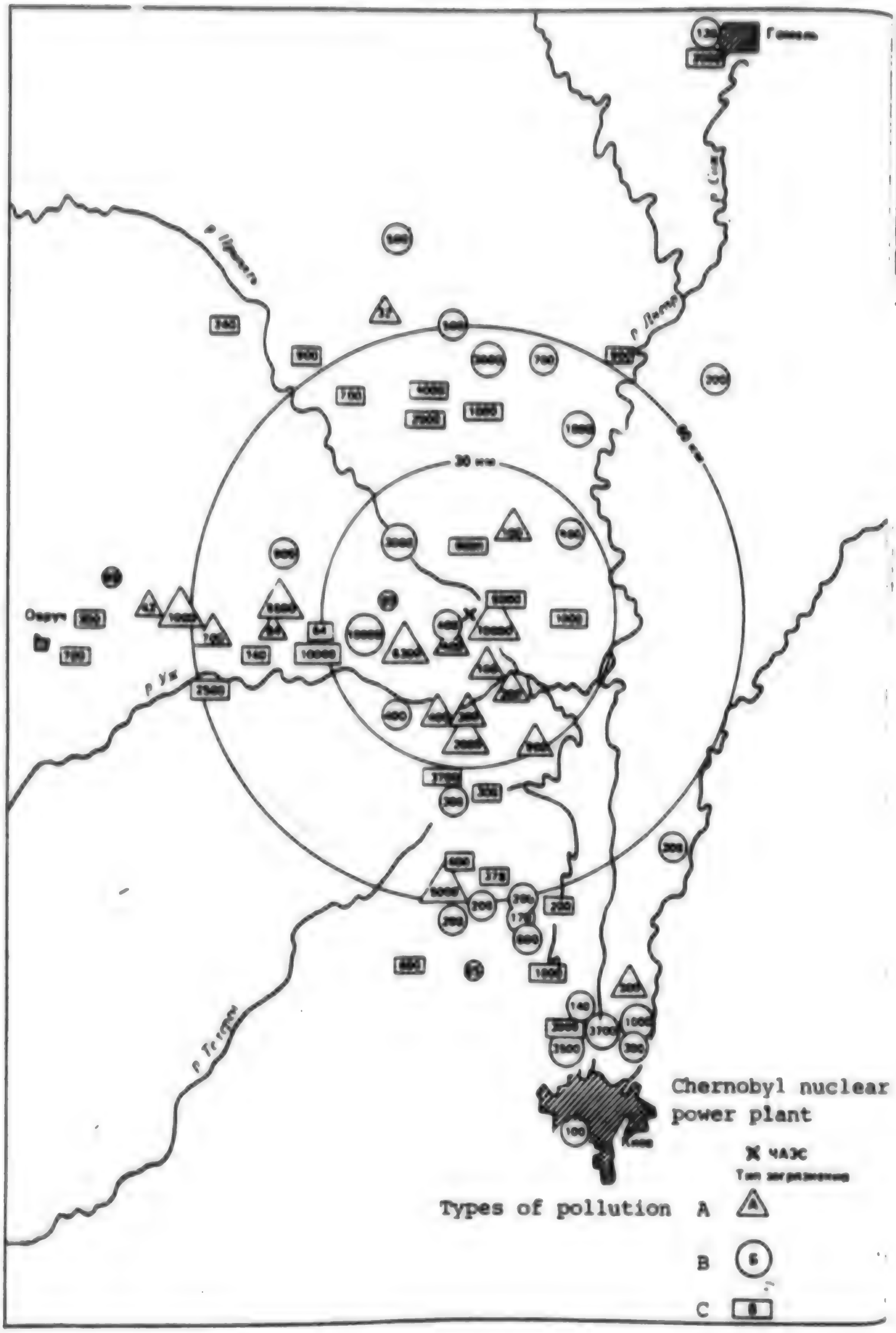
927N0030D Moscow PRIRODA in Russian No 5, May 91, pp 57-61

[Article by F. I. Pavlotskaya and B. F. Myasoyedov]

[Text] When you today become familiar with the literature on the consequences of the Chernobyl accident (even the specialized literature), the feeling sometimes arises that the problem of artificial radioactivity in the environment arose only together with this tragic event. However, the problem arose about 50 years ago as a result of the propagation over the Earth's surface of the products of experimental nuclear shots in the atmosphere. In 1955 a Scientific Committee on the Effect of Atomic Radiation was established in the United Nations in which, together with other materials, a generalization and analysis was made of data on the entry of artificial radionuclides into the biosphere and the patterns of their redistribution. During the initial period the committee concentrated its main attention on global radioactive fallout after nuclear tests in the atmosphere, but later the emphasis shifted to study of pollution of the environment by nuclear reactors, nuclear power plants and radiochemical plants processing fuel during their normal operation and in emergency situations.

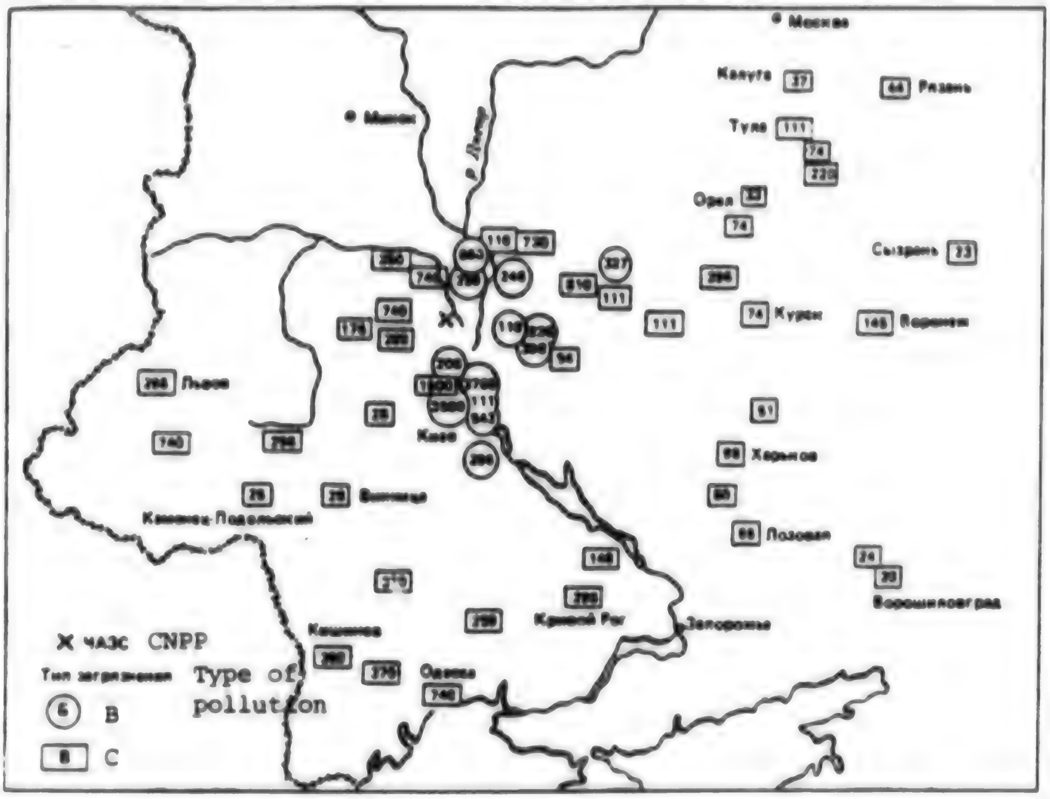
Our institute, already in 1950, became one of the first in the USSR to begin research on artificial radioactivity in the environment. Radiochemical methods were used in determining the content and radionuclide composition of the atmospheric aerosols and fallout. In particular, this made it possible to establish that a hydrogen bomb was detonated by the United States in 1954. Later methods were developed for combined radiogeochemical and radioecological investigations which made it possible not only to determine the content, but also to study the forms of receipt of artificial radionuclides at the Earth's surface, the forms of their presence in soils and the behavior of different natural zones in the soil-vegetation cover.

The Radiochemistry Laboratory of the Geochemistry and Analytical Chemistry Institute (GEOKhI) on the first day after the accident at the Chernobyl nuclear power station was actively included in the work on determination of the radioactive products of the release in different natural objects at different distances and in different directions from the plant, in this work devoting its main attention to possible pollution by plutonium. First, this is a biologically toxic element having several isotopes with long half-lives (86.6, 6620 and 24 100 years for $^{238}$Pu, $^{240}$Pu and $^{239}$Pu respectively). Second, not many organizations in our country can determine its content in the environment due to




Plutonium content (Bq/m²) in soils in 30- and 60-km zone of Chernobyl nuclear power station plant for different types of pollution.

the difficulties in its segregation from the samples of complex chemical and radionuclide composition to be analyzed in a radiochemically pure state and subsequent measurement using radiospectrometers.




Plutonium content in soils of European USSR.

From early May 1986 through June 1988 468 soil samples were analyzed. These samples were taken both in the near zone of the Chernobyl nuclear power plant and in other regions of the European USSR [See Footnote 1]. The total area of the investigated sectors was approximately 1 million $km^2$. The plutonium content was determined in 189 of these. In each analysis it was not only the total alpha-activity which was measured, but also its spectrum, determining the relation between plutonium isotopes.

Radioactive fallout, aerosols, river waters and soils were investigated, but we emphasized soils because most of the plutonium (up to 80-99.9%, depending on the type of biocoenosis) was concentrated in them. In addition, the soil is the initial link in biocoenotic chains, including food chains.

The first samples for analysis were taken during the period 30 April-6 May 1986 by specialists of the Tayfun Scientific Production Association

from the upper soil layer with a thickness 1 cm because precisely this layer after the accident contained fallout radionuclides. Beginning in June 1986 samples also were taken by specialists of the permanently operating radiogeochemical expedition of the GEOKhI using a ring with a diameter 14 cm and a height 5 cm using the standard method approved by the USSR State Committee for Hydrometeorology and Environmental Monitoring.

The data cited on the maps show that the plutonium concentration in the soils differs from the global background caused by the products of nuclear tests and in the northern hemisphere constituting 30-560 Bq/$m^2$, up to 3700 Bq/$m^2$ (0.1 Ci/$km^2$), depending on the distance from the power plant. Thus, over the greater part of the European USSR the plutonium content is far lower than the presently adopted norm (0.1 Ci/$km^2$). A higher plutonium content in the soils was noted only at the power plant and in the alienation zone. The $^{238}Pu/^{239,240}Pu$ ratios in most of the analyzed samples of aerosols, fallout and soils were 0.25-0.35 (averaging 0.3) and were close to the similar value for the nuclear fuel at the time of the accident.

A comparison of data on the plutonium content and fission products in aerosols, fallout and soils with the radionuclide composition of the fuel in the reactor at the time of the accident enabled us, together with I. A. Lebedev, a specialist in our laboratory, and A. A. Khrulev, a specialist at the Atomic Energy Institute imeni I. V. Kurchatov, to discriminate several types of radioactive pollution of environmental features differing in their nature and the ratios of plutonium in them, as well as volatile radionuclides (cesium, ruthenium, barium) and nonvolatile radionuclides (cerium, zirconium, and others): type A -- finely dispersed fuel of unmodified radionuclide composition; type B -- finely dispersed fuel enriched by a factor of 2, 4 and 8 by radionuclides of barium, ruthenium and cesium respectively, as well as plutonium by a factor of 2 in comparison with reactor fuel; type C -- volatile release products greatly enriched with cesium and ruthenium radionuclides (by a factor up to 900 and 80) and by plutonium by a factor of 14 or more.

Pollutants of type A are encountered primarily in the central zone (predominantly in its southern part) and to the west at distances up to 60-70 km, B -- for the most part not more than 100 km, C -- 150 km or more from the Chernobyl nuclear power plant. The different types of pollutions are attributable to the fact that in the damaged reactor complex physicochemical processes occurred under different thermochemical conditions. In the first stage there was primarily a release of fuel particles; later, due to the combustion of graphite, there was a partial fusion of the fuel and construction materials, as well as the decomposition and fusion of the "quenchers" (lead, boron, calcareous rocks, sand, etc.) thrown into the reactor, which was accompanied by the formation of different compounds, including volatile compounds (both radioactive and stable).

In order to predict radiation conditions it is insufficient to have data only on the level of pollution of the Earth's surface, in particular, by

plutonium. It also is necessary to establish the regularities of its behavior in soils, such as the nature of distribution with depth. Earlier, in collaboration with T. A. Goryachenkova and others, it was established that the plutonium falling on the soil-plant cover with global radioactive fallout, at the time of the accident in the Southern Ural in 1957 and from other sources, is included in the biogeochemical migration cycles. This results in its redistribution in the landscape and in the soil profile. Accordingly, in addition to determination of the total plutonium content in soils we also investigated its distribution with depth. It was found that the plutonium entering the environment after the accident at the Chernobyl nuclear power plant also was migrating into the depths of the soil. After 4-5 months, although in small quantities (less than 10% of the initial content) it was discovered at depths up to 3-5 cm, depending on the type of soils and vegetation. In soils with a high content of carbonates plutonium was observed most of all not in the surface 2-cm layer, but at a depth 1-3 cm, which is attributable to its migration in the form of soluble complex compounds with carbonate ions. After scrubbing of columns with such soils in the laboratory by melt water in a quantity corresponding to the depth of the snow cover in this region, about 7% of its initial content in the soil was removed from a 5-cm layer.

Fifteen months after the accident in nonhydromorphous soils polluted by finely dispersed fuel enriched with volatile release products (type B), the maximal quantity of plutonium (73-92%) was retained in the upper 2-cm layer, but it also was detected at a depth of 10 cm. Its most intensive migration occurred in soddy-podzolic soil.

In hydromorphous soils, with a high moisture content and containing high concentrations of water-soluble natural organic substances, which form soluble complex compounds with chemical elements and radionuclides, plutonium was detected even at depths 15-20 cm. An increase in its migration in these soils is favored, in particular, by anaerobic conditions (when tetravalent plutonium is reduced to more mobile trivalent plutonium). In addition to the removal of plutonium from the surface horizon of the soils its secondary accumulation in the upper part of the illuvial horizon is noted, which we observed earlier for plutonium arriving at the Earth's surface from other sources. Iron, one of the principal nonisotopic carriers of plutonium during its geochemical migration in soils of the forest and wooded steppe zones, transported from the above-lying layers, also is accumulated in this horizon.

Our estimates of the possible removal of plutonium from the upper 5-cm layer over a long period of time (more than 20 years) after pollution of different types of soils by global radioactive fallout, during the accident in the Southern Ural, and also other sources of radionuclides, vary in the range 0.9-3% per year. The maximal removal is noted from the litter and poorly developed sod, and also from moist soils with a high content of carbonate ions. However, transfer from the upper layer of nonhydromorphous soils polluted from the accident at the Chernobyl

nuclear power plant is possible at the level 1.4-9% per year. (Earlier American researchers estimated the removal of plutonium a year after soil pollution at 10%.)

A comparison of the removal of plutonium from the surface horizons of soils with its accumulation by plants (in plants growing under natural conditions its content is $10^{-5}$-$10^{-1}$ lower than in the soil) and the coefficients of wind uplifting of tiny particles of polluted soil (according to our data, in early June 1986 in the accident zone it was $6 \times 10^{-5} - 2 \times 10^{-6}$ $m^{-1}$) makes it possible to say that the self-purification of the Earth's surface from plutonium, regardless of the sources of pollution, occurs primarily due to its migration into the deeper horizons, in turn determined by the physicochemical properties of the soils and their genetic structure, type of vegetation, forms of presence of plutonium in the soils and other natural factors.

The estimates of the intensity of plutonium migration in the depths of soils indicated that depending on the factors cited above plutonium may be detected at depths of 40-100, 50-60 and 100-440 cm after 25, 50 and 100 years.

Footnote

1. Radiochemists, soil scientists, biogeochemists and specialists in the field of $\alpha$-spectrometry participated in the work: I. A. Lebedev, V. Ya. Frenkel, V. V. Yemelyanov, T. A. Goryachenkova, Z. M. Fedorova, Ye. M. Korobova, I. Ye. Kazinskaya, Yu. P. Novikov, S. A. Ivanova, T. I. Bukina, G. A. Pribylova, and others.

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## Chernobyl Forest

927N0030E Moscow PRIRODA in Russian No 5, May 91 pp 61-69

[Article by G. M. Kozubov and A. I. Taskayev]

[Text] A wide range of radioecological research on natural ecosystems damaged by radiation over great areas is necessary for developing scientifically sound long-range predictions of radioecological conditions in the neighborhood of the Chernobyl nuclear power plant.

Here a highly important role in the absorption and redistribution of radionuclides is played by forest ecosystems. About half the territory in the 30-km zone around the nuclear power plant is occupied by forest. More than 80% of these forests are conifers, for the most part consisting of Scotch pine (Pinus sylvestris). Individual sectors are occupied by expanses of Norway spruce (Picea abies).

It is known that conifers retain well different atmospheric aerosol pollutants, including radioactive pollutants, but at the same time are some of the most radiosensitive plants (under definite conditions pines already perish from a dose of 600 R [See Footnote 1]). Such a sensitivity of conifers, on the one hand, is attributable to the multiyear period of vital functioning of conifer needles, the great volumes of nuclei and chromosomes in cells, and on the other hand, the specifics of metabolic processes.

It is assumed that the radiosensitivity of organisms increases as their organization becomes more complex, that is, with ascent on the evolutionary ladder. However, conifers, whose genealogy goes back more than 250-300 million years, in their resistance to radiation are extremely close to highly organized warm-blooded animals. The resistance of deciduous species (birches, aspens, willows, oaks), however, is greater by a factor of 10-15. Mosses and lichens, the lethal dose for which is 200 000-500 000 rad, are characterized by a high resistance. The increased radiosensitivity of conifers suggests that during a prolonged interval in the Earth's history (about 0.5 billion years) radiation conditions were close to those of today and if there was an increase in the radiation level it had a local character.

### Radiation Damage Zones

Already the first radioecological investigations initiated by specialists of the Biology Institute, Komi Scientific Center, Ural Department, USSR Academy of Sciences, in the accident region in May-June

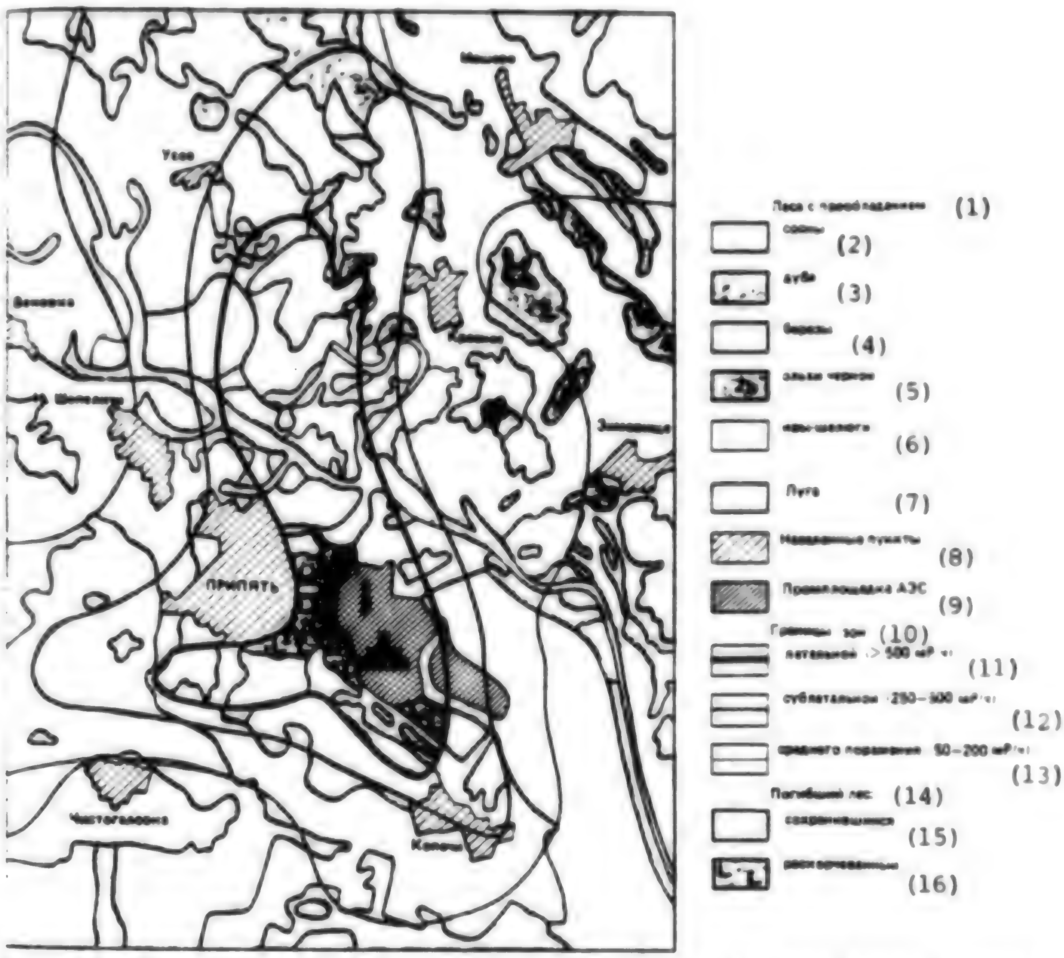
1986 indicated that conifer forests suffered most greatly from radiation. Pine, as the principal woody species of the Chernobyl forest, sensitive to radiation impact, was taken as the main object of study. Four principal zones were defined on the basis of the degree of damage to pine in the 30-km zone of the Chernobyl nuclear power plant at the end of the growing season of 1986.

Dead pine forest near Yanov village (May 1989). Intensity of absorbed dose (everywhere on 1 October 1986) -- 8000-10 000 rad.

All the trees, both young and those 60 to 100 years old, perished in the zone of lethal damage. This is the so-called "reddish forest," where the absorbed dose on 1 October 1986 was 8000-10 000 rad. The total area of the perished pine forests by late 1989 had attained 550-600 hectares, of which two expanses can be discriminated: along the westerly track, extending up to 4-5 km from the nuclear power plant, and northerly (7-8 km from the damaged unit, on the left bank of the Pripyat River). Here the deciduous trees also suffered in part; these were primarily drooping birch, common and northern red oak and European mountain ash, whose tops and individual branches became desiccated, with unusually large leaves with an uncharacteristic dark green intensive coloration appearing on many branches; there was a considerable decrease in growth with respect to trunk diameter.

Zone of sublethal damage, whose boundary for the most part is parallel to the boundary of the first zone (absorbed dose from 800 to 2500 rad).

Here there are two "spots" with increased radioactive pollution: near Dibrova village (to the southwest of the nuclear power plant) and near Kryukovo village in Belorussia (to the northeast). The total area of the damaged pine forests in this zone was about 3700 hectares. The degree of damage was different, depending on the magnitudes of the exposure and absorbed doses, as well as on the age and physiological state of the trees, soil and hydrological conditions.




Zones of radiation damage of coniferous forests in accident region (scale 1:100 000). Isolines of exposure doses as of 1 June 1986. Map compiled using materials provided by V. S. Davydchuk, G. M. Kuzubov and Yu. D. Abaturov in 1990.

KEY:

1. Forests with predominance of...
2. pine
3. oak
4. birch
5. black alder
6. willows, including sharp-leaved willow
7. Meadows
8. populated places
9. Nuclear power station site
10. boundaries of zones
11. lethal (> 500 mR/hour)
12. sublethal (250-500 mR/hour)
13. average damage (50-200 mR/hour)
14. Killed forest
15. still standing
16. stubbed

Young trees and weakened expanses of trees on poor sandy soils suffered most. Radiation "burn" was manifested particularly clearly at forest margins and in thin forests. A high percentage of the young sprouts perished, there was a massive necrosis of growing points and locally the needles became desiccated, primarily in the lower part of the crown. On many trees near the boundary of the "reddish forest" needles remained only on individual branches. In 1986 most of the pines manifested no linear growth increment. However, already by autumn virtually all the trees remaining viable exhibited lateral buds, primarily due to growing rudimentary buds on shortened shoots, which ensured a recovery of growth during the growing season of 1987.

In the zone of intermediate damage (absorbed dose 300-500 rad), as in the entire 30-km zone, radioactive pollution was spotty, extremely nonuniform. The total area of the coniferous forests here is about 12 000 hectares. As in the sublethal zone, the radiation damage to forests is dependent on the radiation and ecological factors and is expressed differently. Suppression of plant growth, death of growing points on apical shoots, growth or partial shedding of needles on the shoots, decrease in the sowing qualities of the seeds and increments in trunk diameter and formation of different morphoses, were observed, especially during the 1987 growing season.

The lack of reliable data on radiation conditions on the first days and hours after the accident does not make possible an unambiguous estimate of the total absorbed doses in one forest sector or another. In this case a retrospective analysis is ineffective. For example, in the spring of 1990 the intensity of the exposure doses for gamma radiation at the soil surface in the lethally damaged forest stands along the westerly track varied from 6 to 50 mR/hour, but along the northerly track -- 4-5 mR/hour. Here a significant role also was played by the composition of radionuclides in the first, most active period of their release from the damaged reactor. In all probability the fate of the damaged forest expanses was sealed by an acute ("shock") irradiation during the passage of vapor-gas-aerosol clouds, whose radiation background attained thousands of rad. However, a study of the reaction of coniferous forests to radiation in the accident region makes it possible to postulate an inadequacy of the degree of damage of pine and intensity of the exposure doses in different parts of the 30-km zone.

The zone of a weak radiation effect (absorbed dose 50-100 rad) takes in virtually all the forest in the 30-km zone and the regions adjacent to it. Here there is no external evidence of morphological impairments, but in 1986-1987 a decrease in the germination of seeds and chromosomal anomalies in meiosis were noted.

Morphofunctional Reactions

In all four zones and in the control 14 experimental sectors were laid out (11 in expanses of pine and 3 in areas of spruce), within which during 1986-1990 a study was made of the features of morphogenesis of

vegetative shoots, stem growth, biometric indices of needles, their anatomic and ultrastructural organization, annual increment of cellulose determined from trunk radius, as well as reproductive processes. The isotopic composition of radionuclides and total beta and gamma radioactivity of the soil were determined in most of the experimental sectors. At the end of the second year after the accident the main contribution to the total gamma activity of the soil was from $^{144}Ce$, $^{106}Ru$ and $^{137}Cs$ (Table 1). The sectors were situated for the most part along the westerly track and differed with respect to the intensity of beta and gamma radiation by a factor of 10 000, which corresponded to a radioecological series from the zone of weak impact to the "reddish forest."

Table 1

Content of Radionuclides in Upper (1-3 cm) Soil Layer in Experimental Sectors (in October 1987)

| Номер участка (1) | Поглощенная доза, рад (2) | Суммарная γ-активность, Ки/кг (3) | Парциальный вклад в общую γ-активность, % (4) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Ce | Ru | Sr | Nb | Cs | Cs |
| 1 | 900—1200 | $1,7 \cdot 10^{-5}$ | 45,9 | 28,7 | 2.6 | 5,7 | 4,9 | 12,2 |
| 2 | 380—510 | $1,5 \cdot 10^{-5}$ | 46,6 | 16,7 | 1,7 | 3,9 | 6,6 | 24,5 |
| 3 | 80—120 | $3 \cdot 10^{-6}$ | 47,1 | 19,4 | 2,9 | 4,8 | 5,9 | 19,9 |
| 4 | 180—260 | $5,7 \cdot 10^{-6}$ | 46,3 | 22,1 | 2,3 | 5,2 | 5,5 | 19,6 |
| 5 | Контроль (5) | $7 \cdot 10^{-8}$ | 47,0 | 19,9 | 2,5 | 5,2 | 6 | 19,4 |
| 9 | 10 000—12 500 | $2,7 \cdot 10^{-3}$ | 57,4 | 20 | 3 | 8,5 | 3,3 | 7,8 |

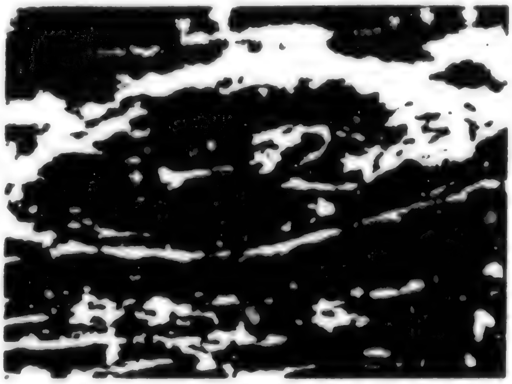
KEY:

1. Number of sector
2. Absorbed dose, rad
3. Total gamma activity, Ci/kg
4. Partial contribution to total gamma activity
5. Control

A spectrometric analysis of pine needles, buds and cones indicated that the composition of radionuclides in all experimental sectors was close to the radioisotopic composition of the soil. In cytological and histological investigations it is necessary to take into account the possible effect exerted on the above-ground organs and tissues by "hot particles" (whose characteristic size is from 1-2 to 40-50 $\mu$m, whereas the activity attains tens of microcurie per particle). In 1986 such particles in individual cases burned unusual funnels on the surfaces of the needles.

The research results show that conifers suffered most of all from acute irradiation during the initial period of the accident, coinciding with the stage of intensive growth of young shoots and the development of reproductive organs. Already with absorbed doses (for gamma radiation) 350-400 rad most of the young vegetative shoots, anthers and female cones perished and the needles in the lower part of the crowns were desiccated. The growth of spruce, birch, black alder and other species was sharply reduced. The maximal suppression of pine growth was observed

in the second year after the accident because in 1986 a considerable reserve of nutrients still remained from the preceding growing season.



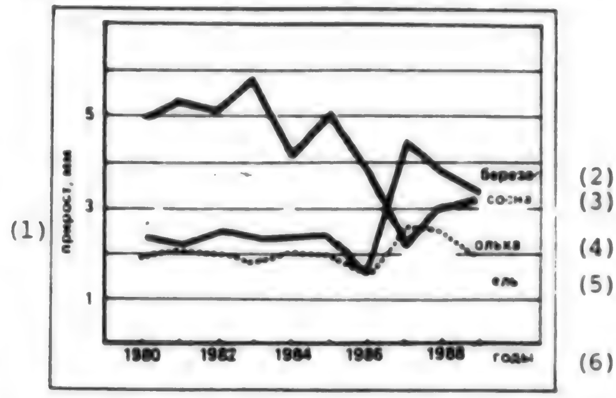



Figure at left: Hot particle on surface of pine needle forming in 1985 (magnification 400).

Figure at right: Increment of cellulose determined from trunk radius for pine, spruce, birch and alder in 1980-1989. Absorbed doses 3000-2500 rad. The minimal increment for spruce, birch and alder was observed in 1986; for pine -- in 1987.

KEY:

| | |
|---|---|
| 1. increment, mm | 4. alder |
| 2. birch | 5. spruce |
| 3. pine | 6. years |

In the reaction of forest ecosystems to ionizing irradiation in the accident region, on the basis of data for four years of observations, it is possible to discriminate three principal periods.

First period (26 April-15 May) -- acute irradiation as a result of the release of fission products during the first hours and days after the explosion when all the short-lived elements, having the greatest biological activity, were "extracted" with a part of the fuel from the reactor. By mid-May all the isotopes of the noble gases and radioactive I had almost disappeared (two half-life periods elapsed) and the contribution of other short-lived isotopes had decreased. However, the radiation damage of forests, especially conifers, was most severe. By the end of the period the release of radionuclides from the destroyed reactor had decreased, although the pollution of territory in the near zone of the nuclear power station still remained extremely high.

Second period (15 May-August-September) -- chronic irradiation of forest ecosystems with high intensities of ionizing radiation. During this time the intensity of the exposure doses on the soil decreased by a factor 4-5, but in individual sectors -- even more. In zones of sublethal and intermediate damage the growth of individual shoots continued, needles were formed and partially died off and the young reproductive buds

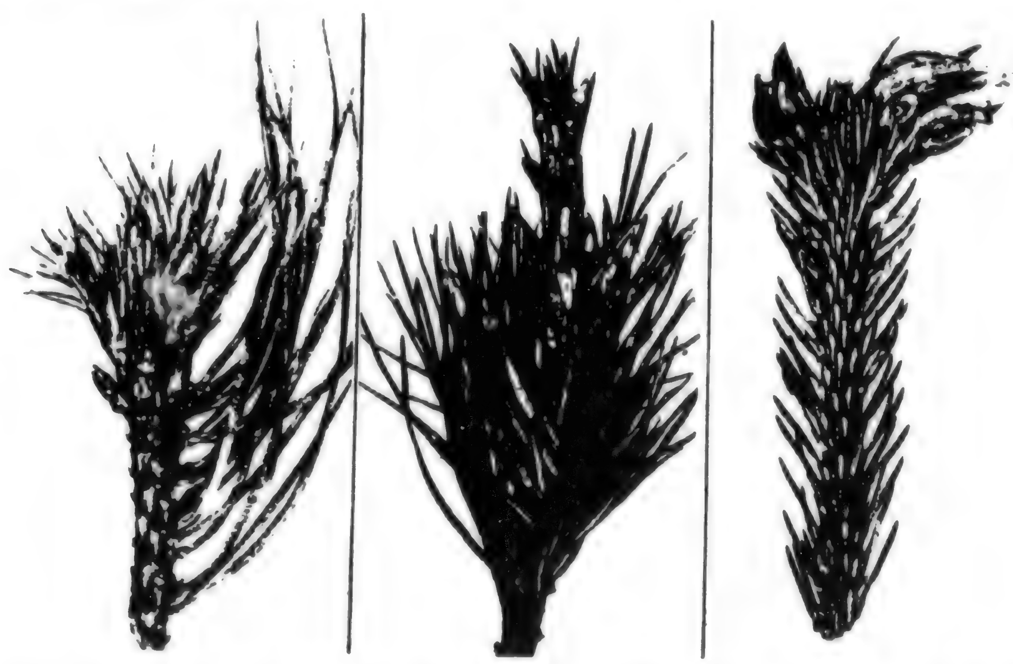
almost completely fell off. The universal growth lag resulted in the formation of greatly shortened and thickened shoots with short bunched needles. Replacement lateral buds were formed on many shoots (even on highly damaged, but still viable pines and spruces). On some of the trees in the zone of intermediate damage a great many large buds appeared and the transformation of bud scales into leaflike formations, growth of secondary shoots, different anomalies in the form and size of the needles were observed.

Greatly shortened shoots of pine forming in 1986. At left: curved shoot with replacement buds; at right: raceme of shortened shoots with unusually dense needles. Here and below -- absorbed dose 300-400 rad.

Impairments in the spatial orientation of the shoots and the rhythm of growth were most likely caused by definite shifts in the hormonal system of the plants. The actively dividing cells of the meristem are the most vulnerable to radiation impact. Their damage, possibly, became the cause of suppression of the synthesis of auxins, localized in the formative tissues. The appearance of different atavistic indicators (growth of bud scales, formation of buds of elongated shoots in place of shortened shoots, etc.) apparently was related to the activation of genes "at rest." The second period was completed by the formation of potential prerequisites for the activation of recovery processes in the coming year.

The third period, whose onset was in April-May 1987, was characterized by a rapid increase in recovery processes, primarily due to intensification of growth of the above-ground vegetative organs: stems and leaves. At this time the radiation conditions began to be

stabilized: the exposure doses were considerably reduced (in comparison with the first period by a factor of 10 or more), as was the increase in the total absorbed doses due to chronic irradiation. In 1987 in sectors with absorbed doses 250-400 rad the pines and spruces exhibited distinct morphogenetic deviations. "Gigantic" needles (greater than normal by a factor of 8-10) were formed on most pines and spruces. In 1987 such gigantism also was exhibited by a number of deciduous species. In the second half of the growing season of 1987-1988 in all the experimental sectors (even with absorbed doses up to 2000-2500 rad) male and female reproductive buds were formed; the male generative level was displaced upward by 2-3 m. In 1987 the synthesis of auxins was intensified and gene repair was normalized.



Anomalous pine and spruce shoots forming in 1986, At left -- outgrowth of bud scales into leaflike formations; in middle -- secondary shoot forming in the autumn of 1986, lateral buds formed in place of pairs of needles; at right -- apical shoot of spruce with growth of small needles clinging to bud into scalelike structure.

Recovery processes continued in 1988 and 1989; even for the highly damaged trees on the boundary with the "reddish forest" there was a rapid increase of the mass of needles and length of shoots. However,the total productivity of pine tree stands by 1989 still had not attained the norm, although it has increased considerably in comparison with 1987. The vegetative shoots of spruce manifested a greater radio-sensitivity than those of pine: already with doses from 70-100 to 150-200 rad there was a considerable decrease in the growth, mass and size of the needles (Table 2).


At top: "Gigantic" needles of spruce forming in spring of 1987. At left -- lateral shoot of spruce 25 years old with normal (a) needles in 1985, shortened needles (b) in 1986 and gigantic needles (c) in 1987; at right -- apical shoots of spruce 10 years old with enlarged straight needles and uncinate, greatly thickened needles.

At bottom: Morphological anomalies of leaves of red oak formed in 1987 (normal leaf at upper left).

The reproductive sphere was the most radiosensitive in pine. For example, with absorbed doses of 70-110 rad In 1987 during meiosis in the microsporocytes the frequency of chromosomal anomalies increased in comparison with the control by a factor of 2-3 (without apparent impairments in the vegetative sphere). In sectors with doses 350-470 rad the viability of pine pollen in this same year decreased to 47.7% (versus 76.2% in the control). The radiation influence was expressed still more strongly in the female sphere [See Footnote 3]: with absorbed doses of 180-260 rad almost 50% of the ovules died off, but with 380-510 rad -- about 75%. In 1986 a proportionality of the percentage of empty seeds to the intensity of the absorbed doses was established.

The pine needles and cones of the second year (developing even after acute irradiation with doses of 1000-2000 rad) were the most resistant to radiation, whereas the most sensitive were young shoots, apical cells of the meristem and reproductive structures. Among the subcellular cytoplasmic organelles the minimum resistance was observed for chloroplasts and mitochondria -- organelles with a complex membrane system. High radiation doses resulted in changes in intracellular structures: sinuous form of the nuclear membrane, broadening of channels in the endoplasmatic reticulum, breakdown of ribosomes, increase in the number of globules in the plastids and protein-lipoid globules in the cytoplasm, impairment in the orientation of chloroplasts and other restructurings of subcellular organization [See Footnote 4].

Table 2

Biometric Indices of Spruce Shoots in Sectors With Different Absorbed Dose

| Год формирования (1) | Прирост верхушечного побега I порядка, см (2) | Кол-во хвои на 1 см (3) | Средняя длина хвои, мм (4) | Масса 100 шт. хвои, г (5) |
|---|---|---|---|---|
| | | 70—100 рад rad | | |
| 1985* | 55,3±2,7 | 12,9±1,0 | 15,9±0,5 | 1,0 |
| 1986 | 30,2±2,5 | 36,6±0,8 | 12,7±0,5 | 0,4 |
| 1987 | 27,7±2,4 | 9,5±[illegible],8 | 21±0,9 | 1,4 |
| 1988 | 40,4±2,8 | 13,6±0,7 | 16,4±0,5 | 1,3 |
| | | 150—200 рад rad | | |
| 1985* | 49,5±2,3 | 14,4±1,5 | 14,3±0,4 | 0,9 |
| 1986 | 20,5±1,5 | 50,0±0,7 | 10,5±0,4 | 0,3 |
| 1987 | 26,8±1,7 | 10,0±1,6 | 21,0±0,8 | 1,7 |
| 1988 | 40,6±2,2 | 14,8±0,5 | 17,6±0,6 | 1,5 |
| | | 300—400 рад rad | | |
| 1985* | 42,6±2,1 | 16,7±2,0 | 13,5±0,6 | 0,9 |
| 1986 | 18,5±1,9 | 40,4±0,6 | 12,6±0,6 | 0,4 |
| 1987 | 32,2±2,4 | 8,7±0,9 | 28,0±1,4 | 2,3 |
| 1988 | 45,8±2,8 | 14,5±0,7 | 18,6±0,8 | 1,9 |

(6)

* 1985 г.— контроль.

KEY:

1. Year of formation
2. Growth of 1st-order apical shoot, cm
3. Number of needles per 1 cm
4. Mean length of needles, mm
5. Mass of 100 needles, g
6. *1985 -- control

## Prediction and Prospects

The research results make it possible to give a favorable prediction for most expanses of conifers retaining their viability up to 1988. However, over a considerable territory of the forests the density of radiation pollution remains rather high, and judging from the stabilization of radiation conditions, this will persist for a long time. Ordinary engineering-technical measures for the deactivation of such forested areas and agricultural lands (that is, uprooting of the forest, stripping of the upper soil layer) are without promise and are economically infeasible. Bioecological approaches may be an alternative. The most correct approach is the conservation of the forest expanses existing in the zone in a natural state and carrying out reconstruction of partially damaged forests and wooded expanses in highly polluted areas of agricultural lands.

The planting of forests is the most economically efficient method for ecological recultivation of the 30-km zone. Indeed, forests are stable ecosystems, a powerful geochemical landscape complex, capable of considerably reducing the migration of radionuclides and the surface runoff of moisture into river systems. Forest plantings virtually preclude the transport of dust and stabilize the radioecological conditions. Such forests will attain commercial maturity after 90-100 years, when the density of pollution decreases sharply, so that the wood can be used in a number of economic branches. However, the principal objective of forest plantings is that the new expanses of forest will play a positive environmental-forming role as an oxygen source, a soil- and wind-protection factor [See Footnote 5]. All this will make it possible to recommend the planting of forests in a radius not less than 30-40 km for establishing an ecological protective zone around nuclear power plants already in existence and those under construction.

Genetic-selection research on the offspring of irradiated trees, natural renewal on polluted territories, selection and study of radioresistant forms of pine and spruce, controllable pollinization, hybridization, physiological-biochemical and morphofunctional investigations of forming modification and mutant forms, should assume particular importance in the future.

### Footnotes

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Combined Mapping of Polluted Territories

927N0030F Moscow PRIRODA in Russian No 5, May 91 pp 69-70

[Article by Ye. M. Korobova, V. G. Linnik, candidate of geographical sciences, and S. K. Novikova, candidate of chemical sciences, Geochemistry and Analytical Chemistry Institute imeni V. I. Vernadskiy, USSR Academy of Sciences]

[Text] During the five years which have elapsed since the accident at the Chernobyl nuclear power plant the problems and approaches to the mapping of polluted territories have undergone considerable changes.

In the first stages of work on eliminating the consequences of the accident, requiring on-line evaluation of radiation conditions, the USSR State Committee for Hydrometeorology and Environmental Monitoring delineated territories with different levels of pollution by long-lived radionuclides. They were represented on topographic maps at 1:500 000.

It has now been several years that there has been constant monitoring of changes in radiation conditions over all the most polluted territories. According to available data, the areas of these expanses and their boundaries have virtually not changed since the accident. This is attributable to the considerable contribution to radioactive pollution from "hot particles" which are not readily soluble and the relatively solid bonding of radioactive cesium in soils, which outside the 30-km zone account for 80 to 100% of the total pollution by artificial radionuclides.

Now the emphasis is on less polluted territories where safe residence and economic activity are possible only with rigorous radioecological monitoring, where any of the types of economic activity requires adaptation with allowance for the natural and anthropogenic factors determining the regional and local characteristics of the distribution and migration of radionuclides.

Such information, necessary both for long-range monitoring and for prediction of radioecological conditions, is reflected on landscape-geochemical maps. These maps, in addition to polluted regions, depict the conditions and factors exerting an influence on the migration of radionuclides in all natural media and the zones of their secondary accumulation are defined. Thus, landscape-geochemical maps constitute a necessary base for preparing radioecological maps, and in the long run, for evaluating the possible entry of radionuclides into agricultural products and correction of the magnitudes of the dose loads as a function of the natural characteristics of the territories.

Unfortunately, for the time being landscape-geochemical maps exist only for individual territories and these in many cases are not predictive. Neither in our country nor abroad is there experience in preparing combined landscape-geochemical maps with a set of parameters necessary for computing local and regional models of the migration of radio nuclides.

On the basis of a decree of the USSR Supreme Soviet entitled "A Unified Program for Eliminating the Consequences of the Accident at the Chernobyl Nuclear Power Plant and the Situation Resulting From This Accident," a decree of the USSR Council of Ministers and the directions of the Presidium USSR Academy of Sciences, a number of scientific and production organizations have been assigned the task of producing combined medium- and large-scale landscape-geochemical and radio-ecological maps for the entire territory polluted by radionuclides. The organization of this work in the field was assigned by the Academy of Sciences to the Geochemistry and Anaytical Chemistry Institute imeni V. I. Vernadskiy, USSR Academy of Sciences (GEOKhI).

The first coordinating conference on the mentioned problem, in which representatives of more than 40 organizations of national and republic level participated, was held in January 1991 at the GEOKhI. The conferees discussed the program for preparing medium-scale (1:200 000-1:500 000) landscape-geochemical and radioecological maps of polluted territories, as well as the fundamental principles for their preparation. The initiators of the project were L. M. Khitrov, V. G. Linnik and Ye. M. Korobova.

In preparing landscape-geochemical maps it is proposed that use be made of available hydrogeological, geomorphological, soils, geobotanical and other branch maps at 1:200 000. They will be used as a basis for preparing republic (1:200 000) and national (1:500 000) landscape-geochemical and radioecological maps of polluted territories. It is proposed that individual sectors -- keys -- be prepared with greater detail (at 1:50 000).

Serious work must be done on the collection and analysis of enormous masses of factological and cartographic information accumulated by the most different departments: State Committee for Hydrometeorology and Environmental Monitoring, Agroprom, Ministry of Geology, etc. It is necessary to generalize all this information and reduce it to a uniform scale, which is impossible without formulating unified mapping principles, criteria and methods.

It is planned that work will begin with the preparation of medium-scale landscape-geochemical maps of conjugate territories in the Ukraine, Belorussia and Russia (Kiev, Chernigov, Gomel and Bryansk Oblasts),. carrying out additional fieldwork here. Later on all polluted territories will be mapped.

In the future plans call for developing a unified hierarchical system for preparing radioecological maps, taking into account all the factors

involved in the migration of radionuclides, and also organize a national bank of radioecological information. Only in this way will it become possible to compare numerous predictive estimates and models of the migration of radionuclides.



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